NOVA

3 B

(HAVO)|VWO TTO

Physics



NAME AND CLASS:

MALMBERG

NOVA

3 (HAVO)|VWO TTO

Physics

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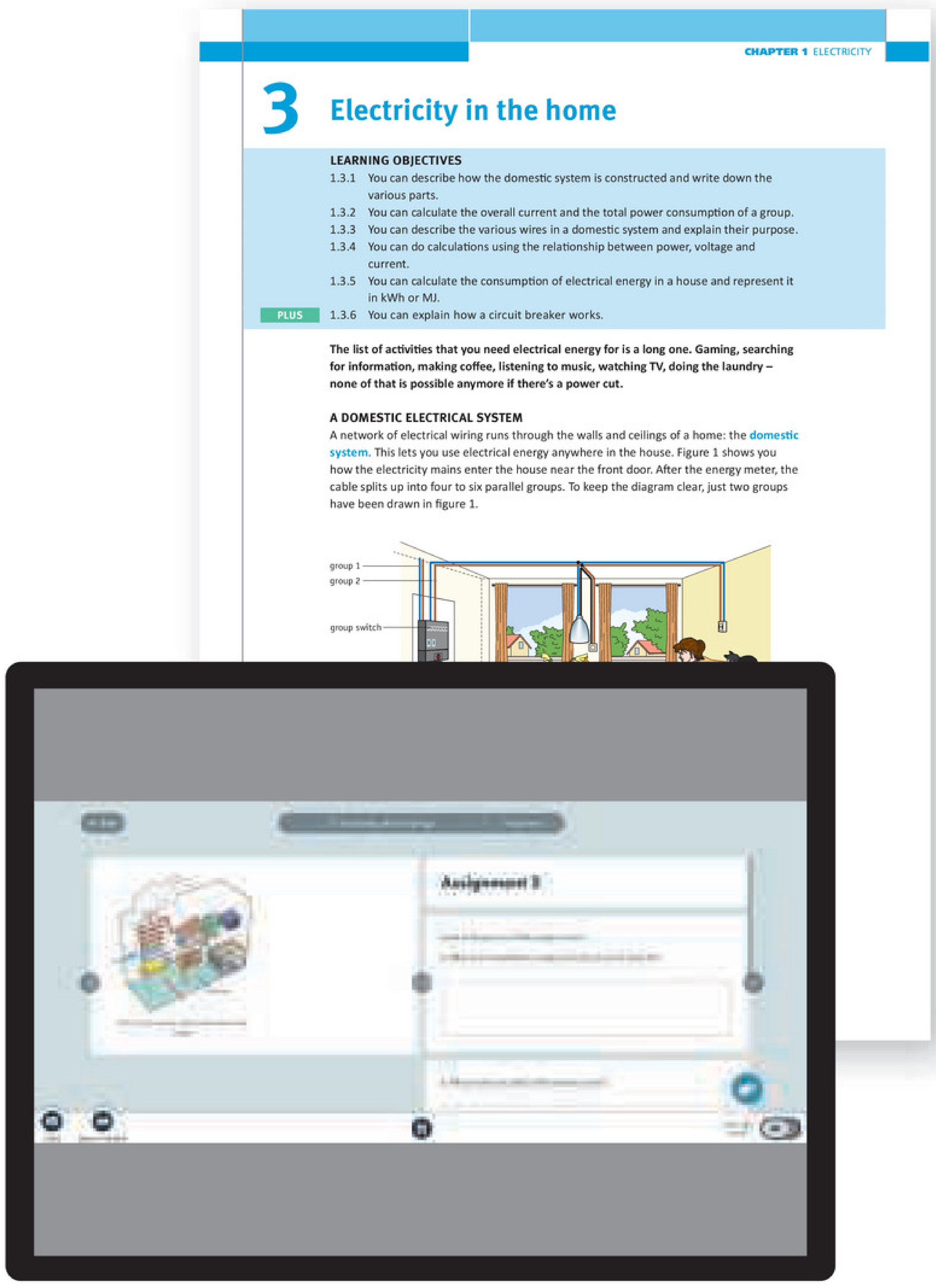
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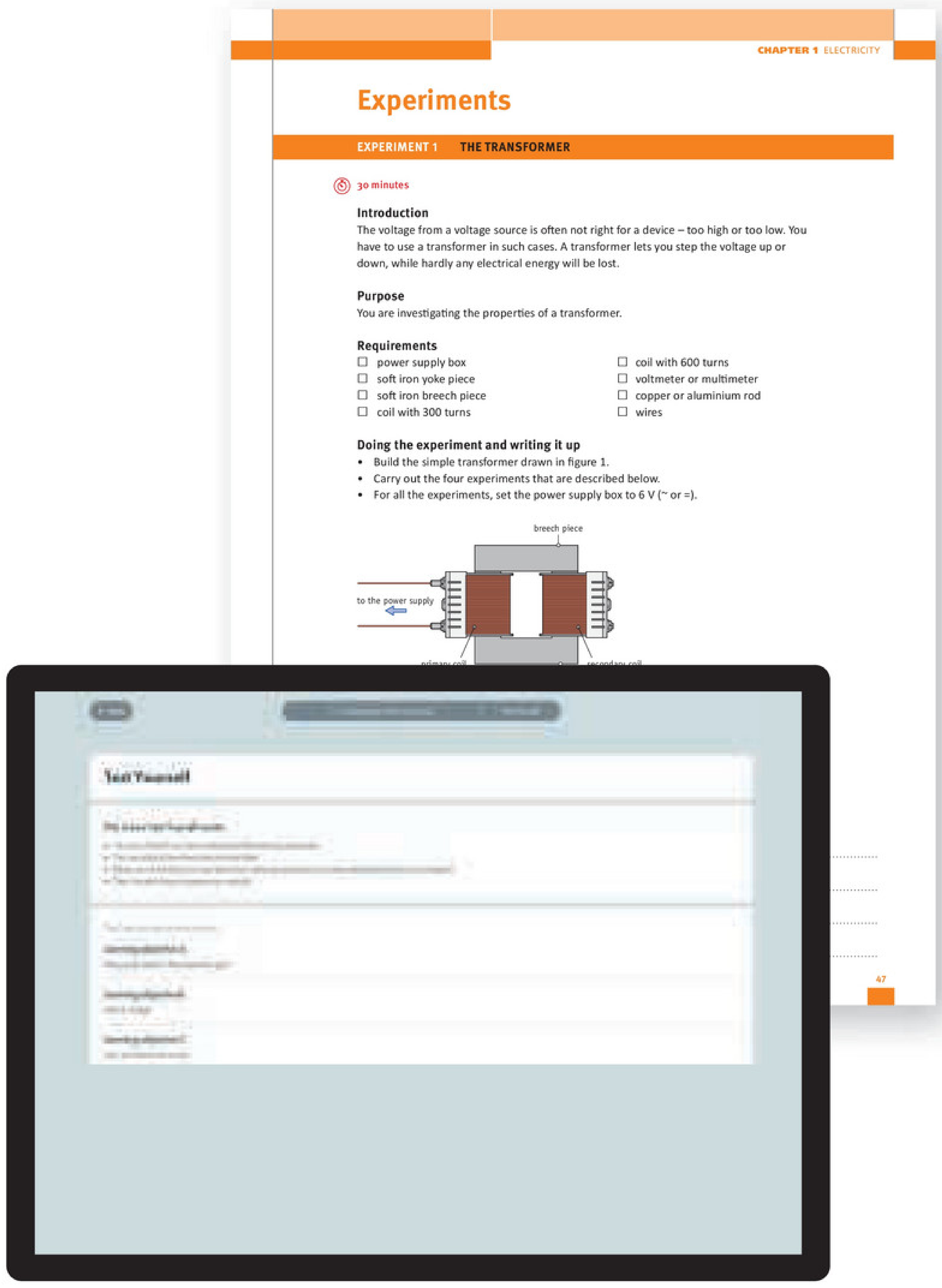
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Getting started with Nova

Why learn with Nova?

Physics is about the world around you. Nova puts all the tools within easy reach that you need for experiencing, enjoying and discovering it!





Work in your book and work online!

There are two books for each school year plus an online learning environment. Your teacher will decide what you do online (with a laptop, tablet or phone) and what you do in your book. You write the answers to the open exercises in your exercise book, not in your book. Each chapter is split up into an introduction that checks what you already know, theoretical sections and a section with practical experiments, an *Everyday science* article and a closing section. Each section begins by stating the learning objectives that tell you what you will be learning about. The extra material lets you see whether physics would be a good subject for you in the later school years. In the experiments section, you will do assignments and learn how to study and investigate. At the end of each chapter, there is an *Everyday science* section, an article in which part of the course material is discussed in practice in a situation from daily life or from a scientific context. The closing part contains the *Remember* and *Definitions and concepts* sections.

The advantages of working online

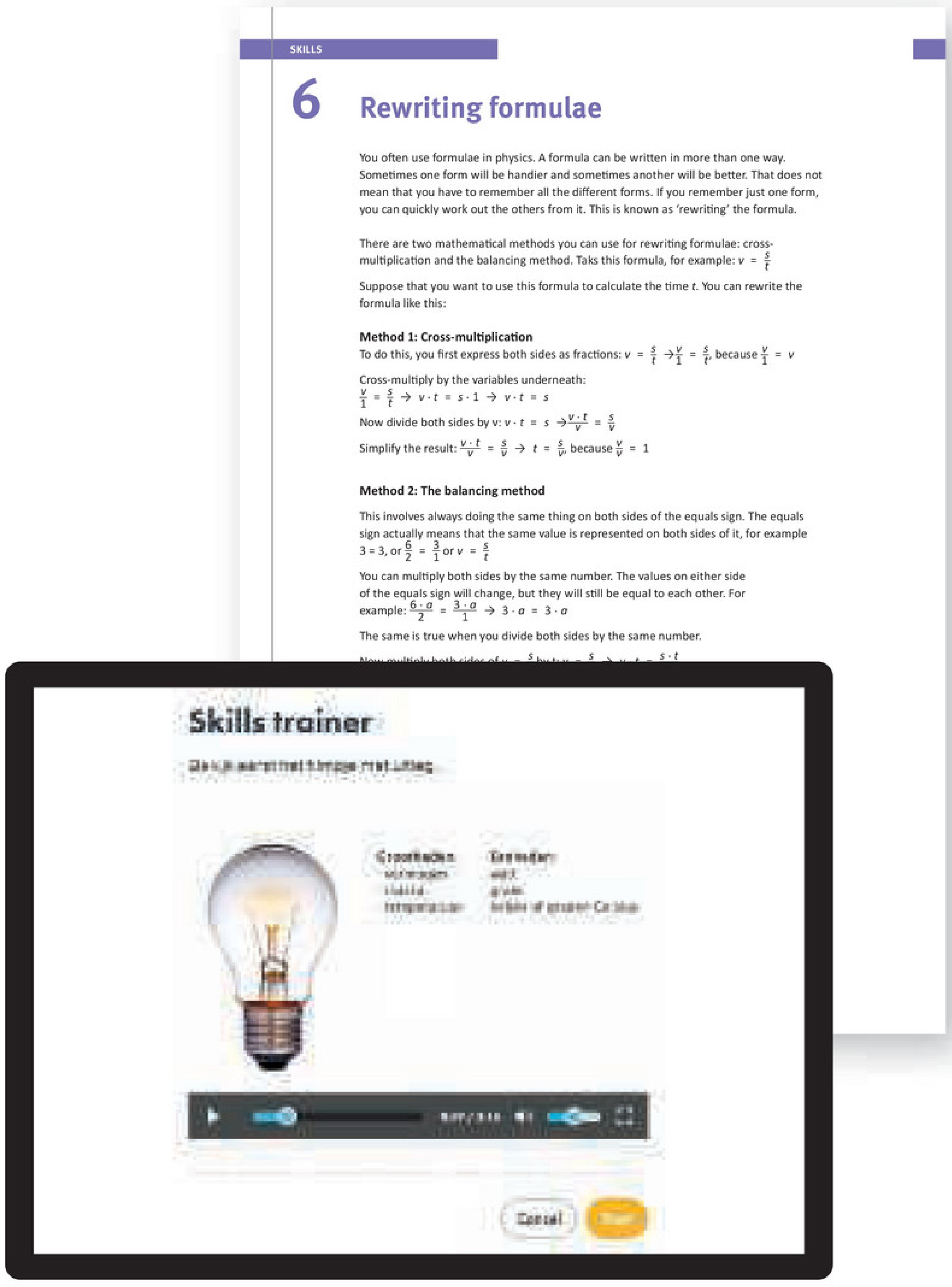
- You will see quickly what you are doing correctly and what you are doing wrong.
- You get feedback on your answers straight away.
- You can watch video clips and animated clips.
- You can practice important skills with the Skills Trainer.
- You learn the concepts using the *Flash cards*.
- You can use the *Test yourself* section, the *Practice test* and the *Diagnostic test* to see how well you have understood the material.
- You can also work with material for a lower level or school year.
- Your teacher will monitor how you are progressing.

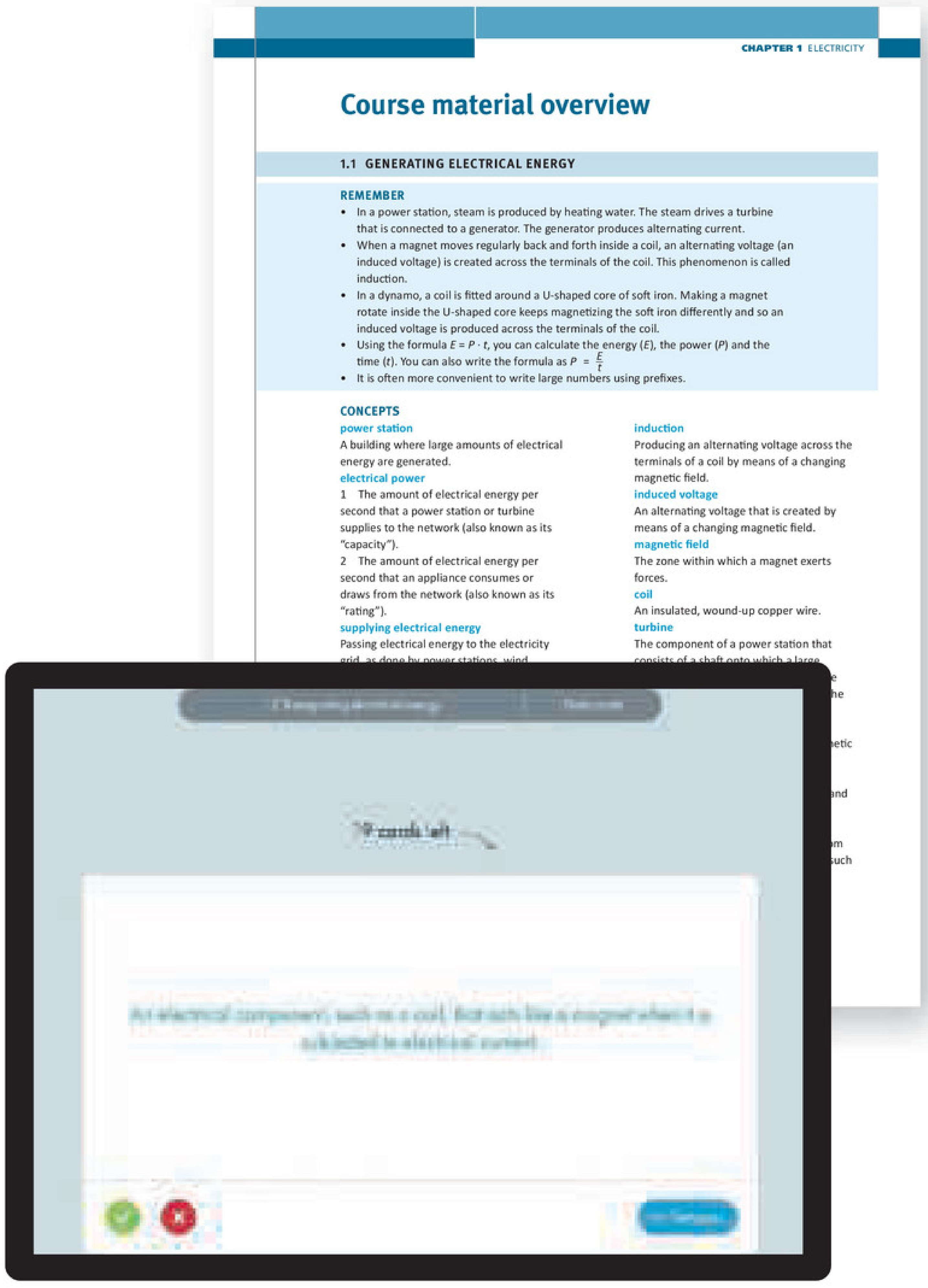
Skills

At the end of each book, you will find a *Skills* section in which the key skills for doing research and investigating are explained. A number of important skills can also be practised online with the *Skills Trainer*.

Good preparation for the test!

The *Remember* and *Definitions and concepts* sections at the end of each chapter in the book will help you prepare for the test. There is a *Diagnostic test* in the *Completion* section online. This is also where you can find the *Flash cards* for learning all the concepts. If you are not sure that you understand the material sufficiently, use the *Test yourself* or *Practice test* parts at the end of each section.





The advantages of the book

- You get a quick overview of what you will be learning.
- You can read the longer texts on paper.
- You can annotate the text and add remarks.
- You write down short answers directly with the exercise.
- You fill in the tables and graphs in the book, just as you do for the results of the experiments.
- You will be making drawings and adding colour yourself, which helps you remember things better.

Meaning of the symbols

Symbol	Meaning
(online icon)	Go to the online learning environment for some useful extras.
EXP. 1	There is an experiment for this classroom material.
(clock icon)	This is how long this experiment will take.
(skills icon)	Use the skills for this assignment.
★	This assignment is extra challenging.

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4 Forces and motion

KEEP MOVING

Whether you are riding a bicycle or driving a racing car, you need forces to create the motion. If you stop pedalling or take your foot off the accelerator, your speed immediately starts to drop. That is because of the resistance forces that work against the direction of your motion.

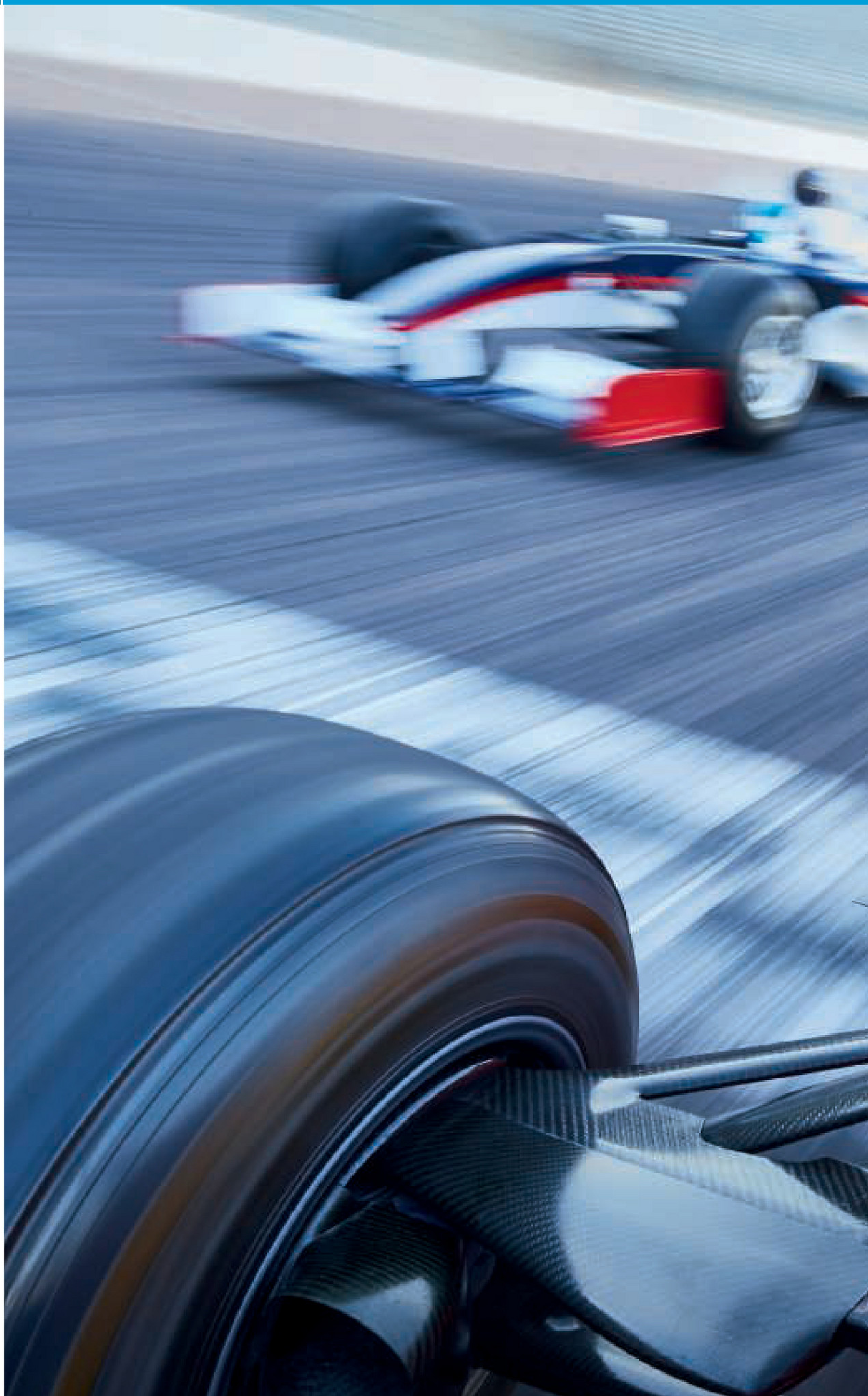
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What do you already know about forces and motion?

LEARNING OBJECTIVES

1 You can read off a speed-time diagram or (v,t) diagram.
2 You can determine the place associated with a given time on a displacement-time diagram or (x,t) diagram and vice versa.
3 You can use the formula for average speed.
4 You can convert an average speed in m/s to km/h.
5 You can describe what the effect is on an object when a force is exerted on it.
6 You can describe various forces.
7 You can calculate the force of gravity exerted on a mass.
8 You can draw a force using a force scale.
9 You can calculate the resultant of forces that act along the same line.

In Parts 1 and 2 of Nova NaSk, you already learned various things about motion. In Chapter 2, you learned various things about forces. You will need this knowledge when you start this chapter. If you want to do a quick check of what you can remember, do the following exercises.

EXERCISES TESTING YOUR PRIOR KNOWLEDGE

1 A snail crawls a distance of 2.36 m up a tree trunk. This takes it 0.45 h.
Calculate the average speed of the snail in m/h.

....

....

....

2 Convert.

10 m/s = ... km/h   30 km/h = ... m/s

0.72 m/s = ... km/h   244 km/h = ... m/s

3 Calculate the gravitational force exerted on a horse with a mass of 550 kg.

....

....

....

4 Determine the resultant acting on the cyclist in figure 1.

....

....

....

5 How is the cyclist in figure 1 moving?

- ○ A The cyclist is accelerating.
- ○ B The cyclist is decelerating.
- ○ C The cyclist's movement is uniform.

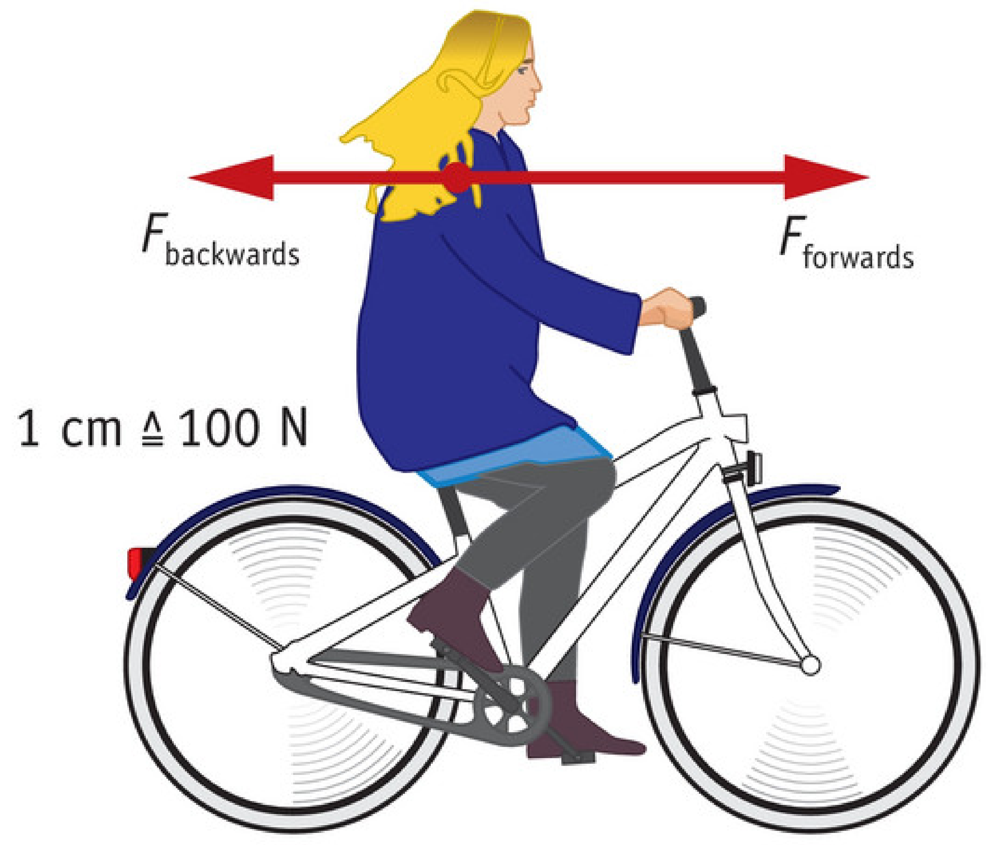


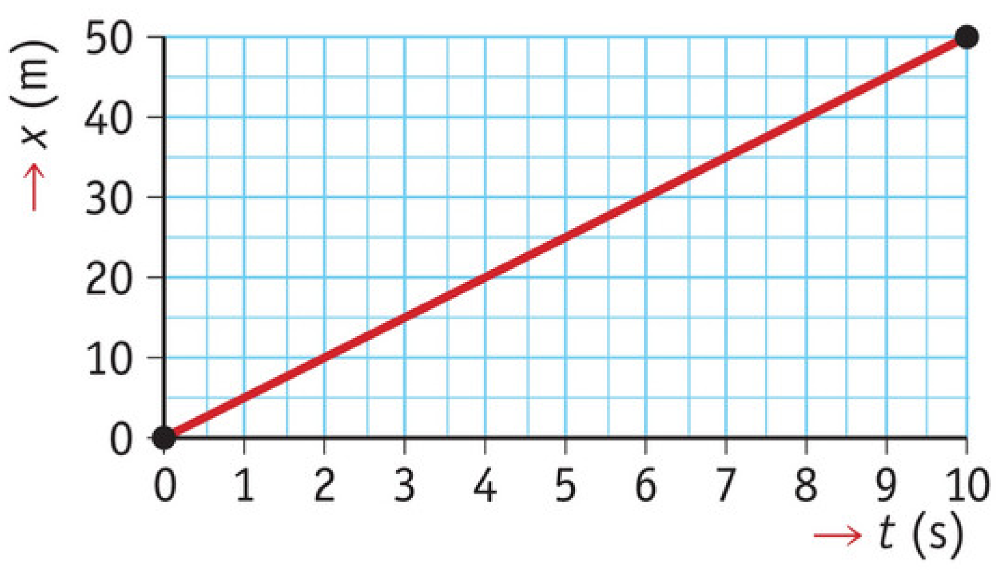
figure 1 Forces on a bicycle.

6 The diagrams on the left and right are of the same motions: left as an (x,t) diagram and right as a (v,t) diagram.
Draw a line from each (x,t) diagram to the corresponding (v,t) diagram.

(x,t)-diagram

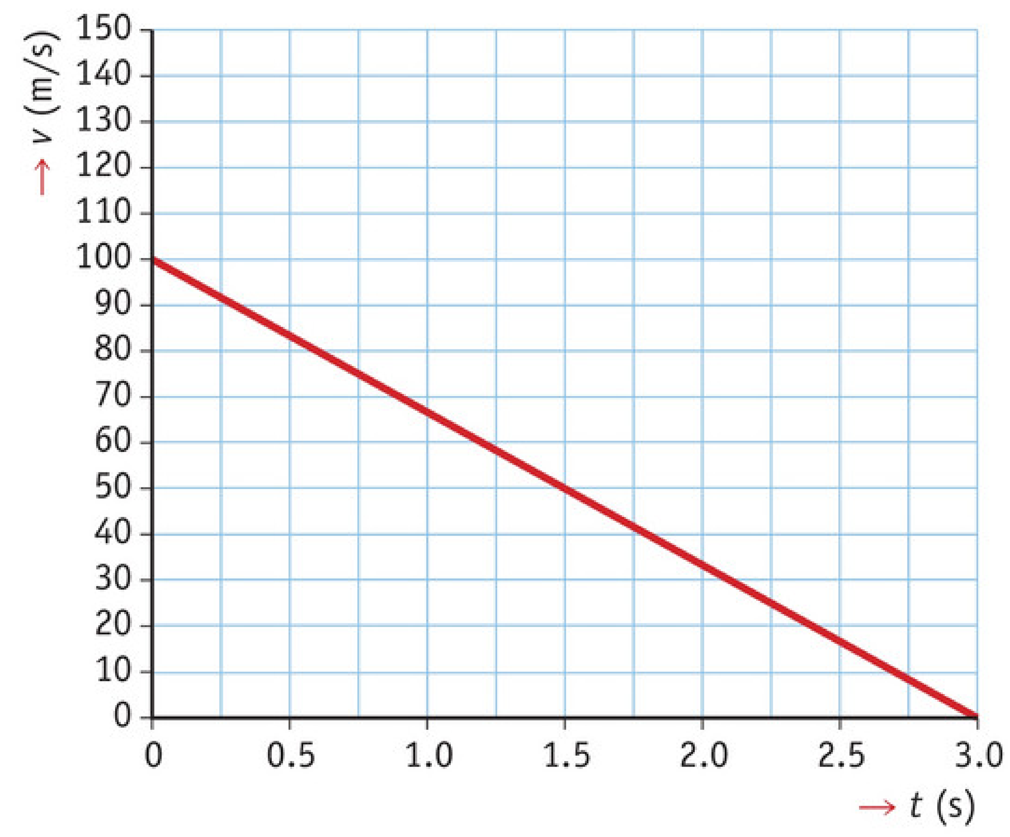
(v,t)-diagram

A

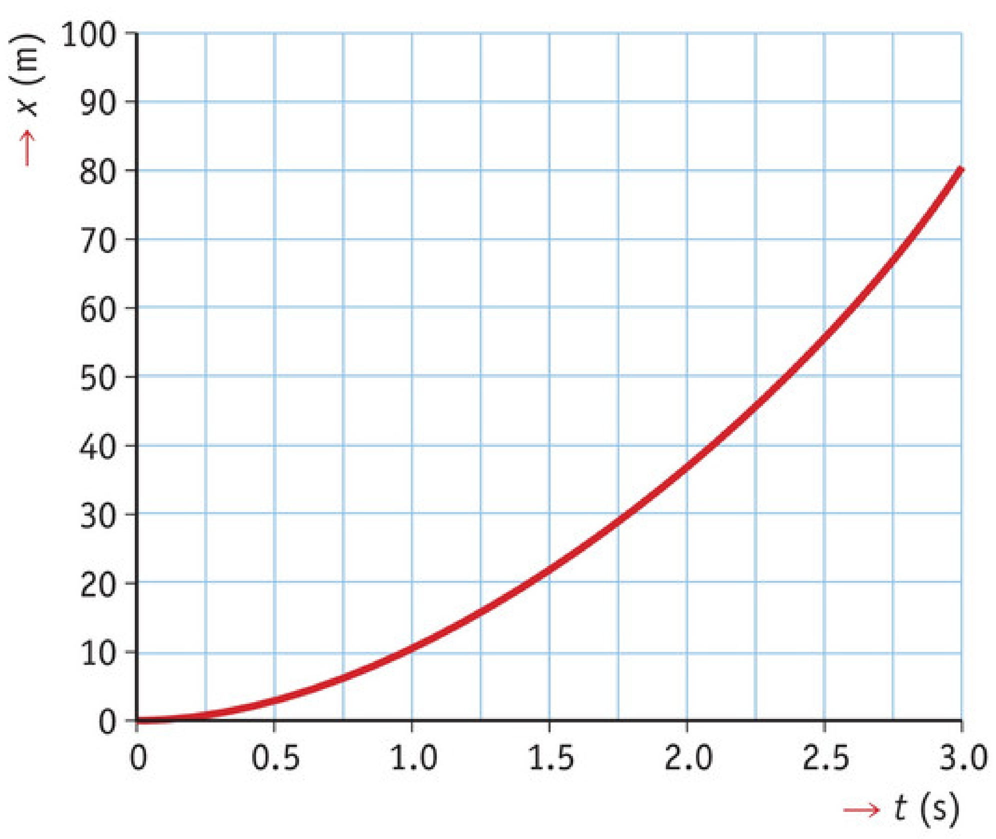


○ ○

1

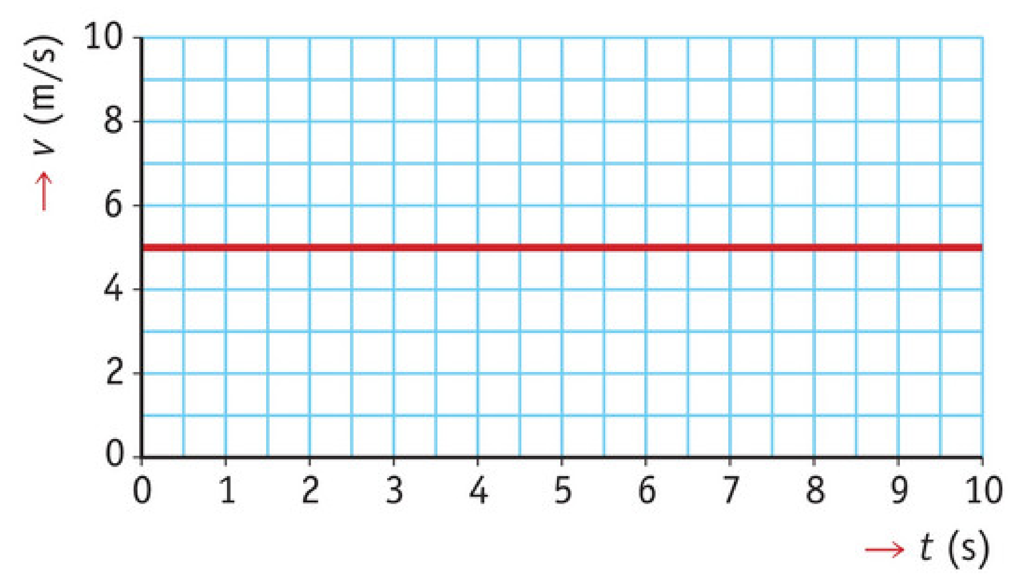


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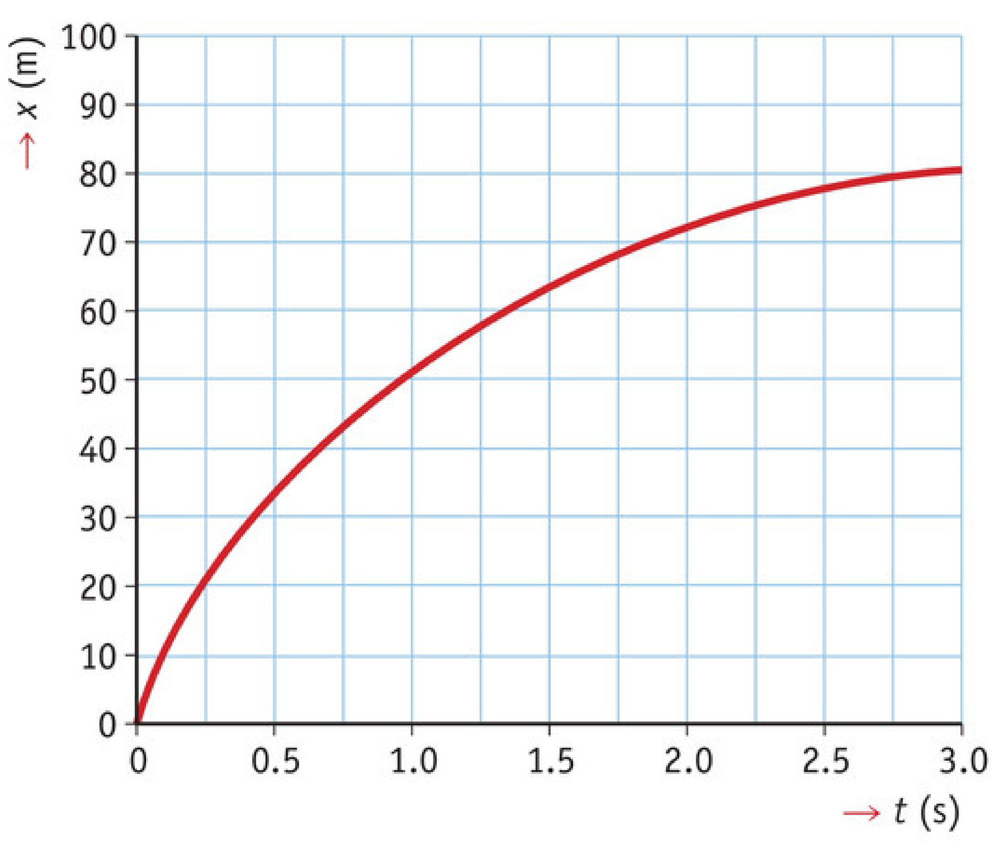


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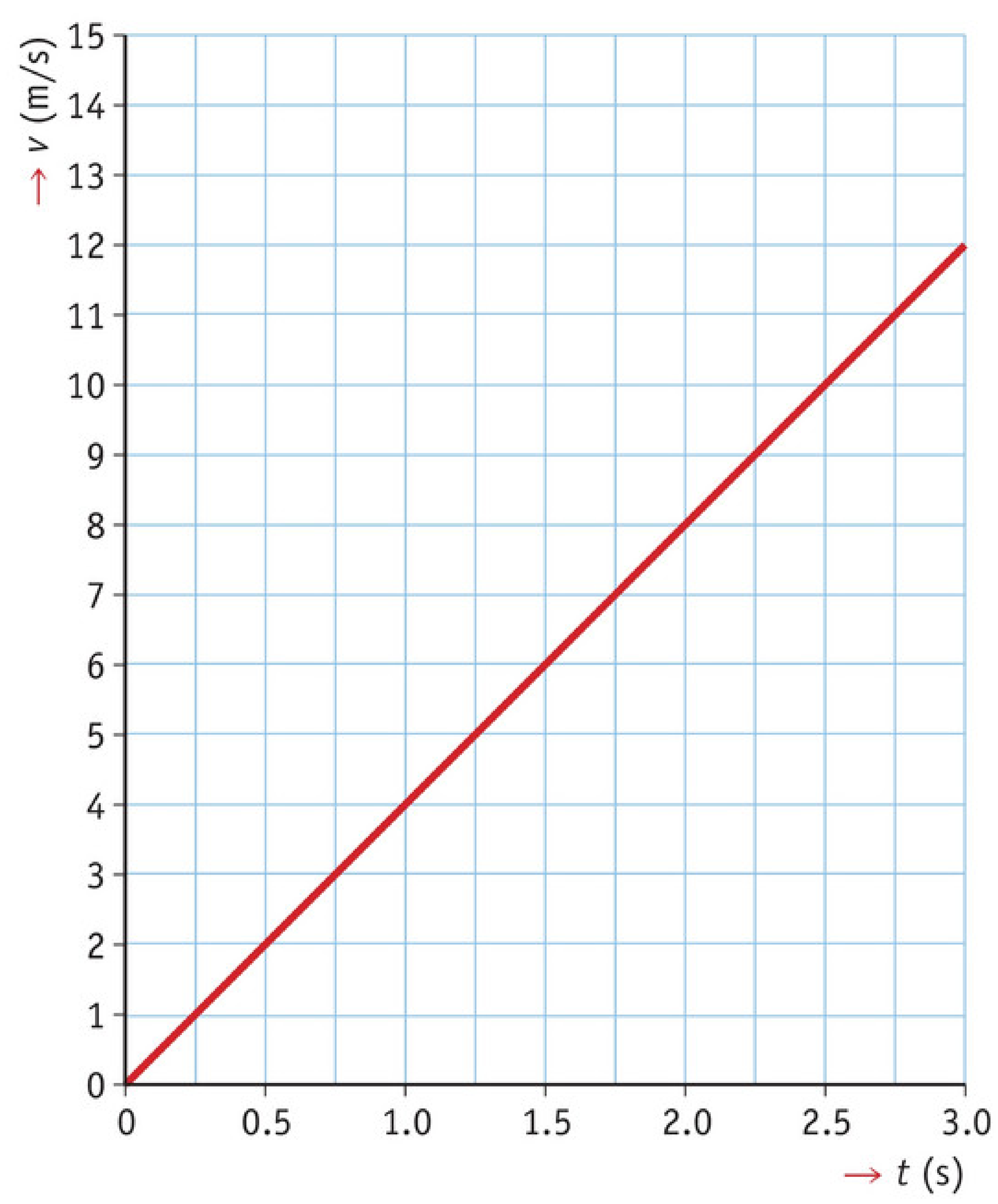


C



○ ○

3



If you want to know whether you have enough prior knowledge for this chapter, you can take the online *Prior knowledge test*. You can also find videos about the key learning objectives for this chapter there.

1 Accelerating and decelerating

LEARNING OBJECTIVES

4.1.1 You can record a motion as a (v,t) diagram and as an (x,t) diagram.
4.1.2 You can use a (v,t) diagram or an (x,t) diagram to determine what type of motion it is.
4.1.3 You can explain how the variables acceleration and deceleration are defined.
4.1.4 You can calculate the acceleration in a uniform acceleration.
4.1.5 You can calculate the deceleration in a uniform deceleration.
4.1.6 You can use the (v,t) diagram of a motion to determine the distance covered.
PLUS 4.1.7 In a non-uniform acceleration, you can use the (v,t) diagram to determine the distance covered and the average speed.

When you are in a plane, you may be flying at a speed of more than 900 km/h. The carriages of a roller coaster 'only' have a maximum speed of perhaps 150 km/h. Yet a ride in a roller coaster feels much more exciting than a flight in an aircraft. This is because the carriages accelerate and brake very quickly. So it seems that it is not actually the speed itself that you feel in your stomach, but the change in speed.

MAKING A (*V*,*T*) DIAGRAM

The speedometer of a car shows how fast the car is going at that particular moment. If you photographed the speedometer at intervals of 1 second, you would get a series of images such as shown in figure 1. From the graph, you can read out what the speed is at times t = 0 s, t = 1.0 s, t = 2.0 s and so on.

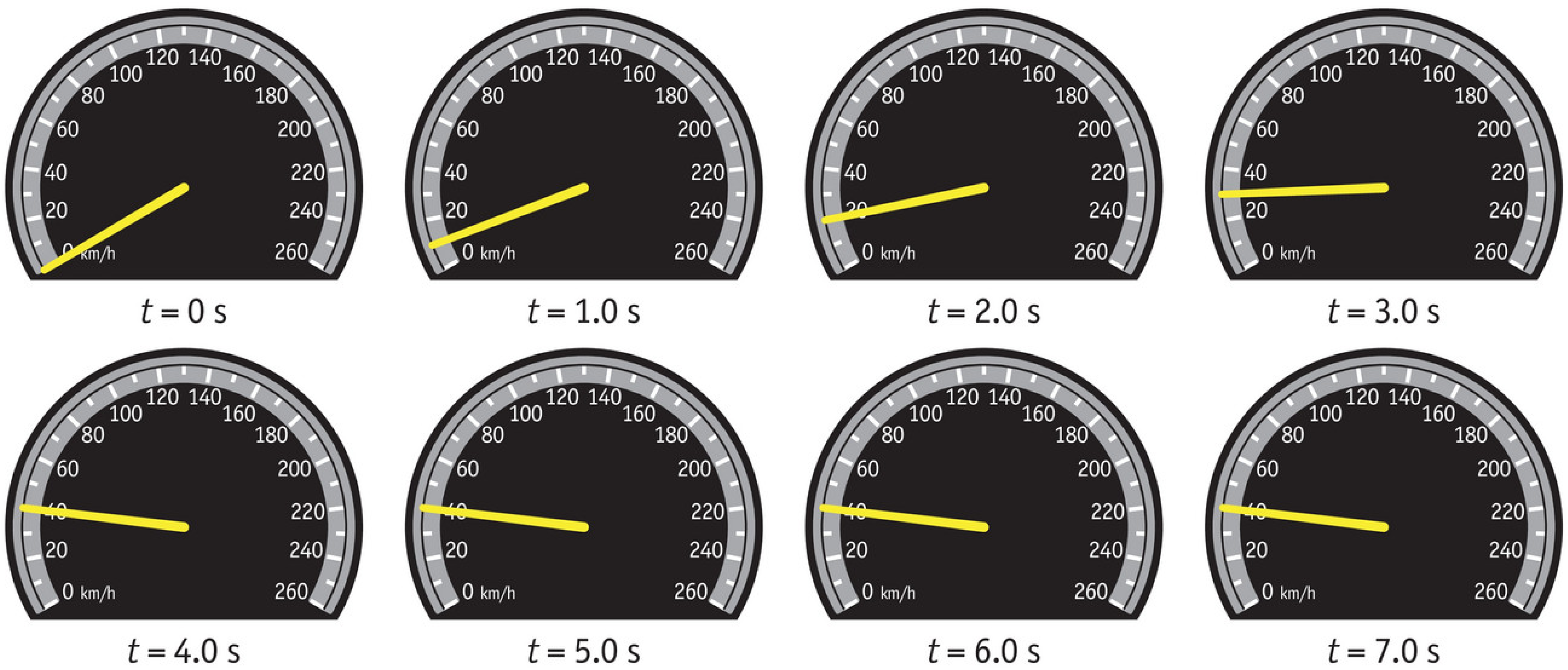


figure 1 The speedometer shows you how fast the car is going.

The **(speed, time) diagram** in figure 2 was drawn using the data from figure 1. A graph like that shows you at a single glance how the entire motion progressed. A (speed, time) diagram is often called a **(v,t) diagram**. The time t is shown along the horizontal axis and the speed v along the vertical axis.

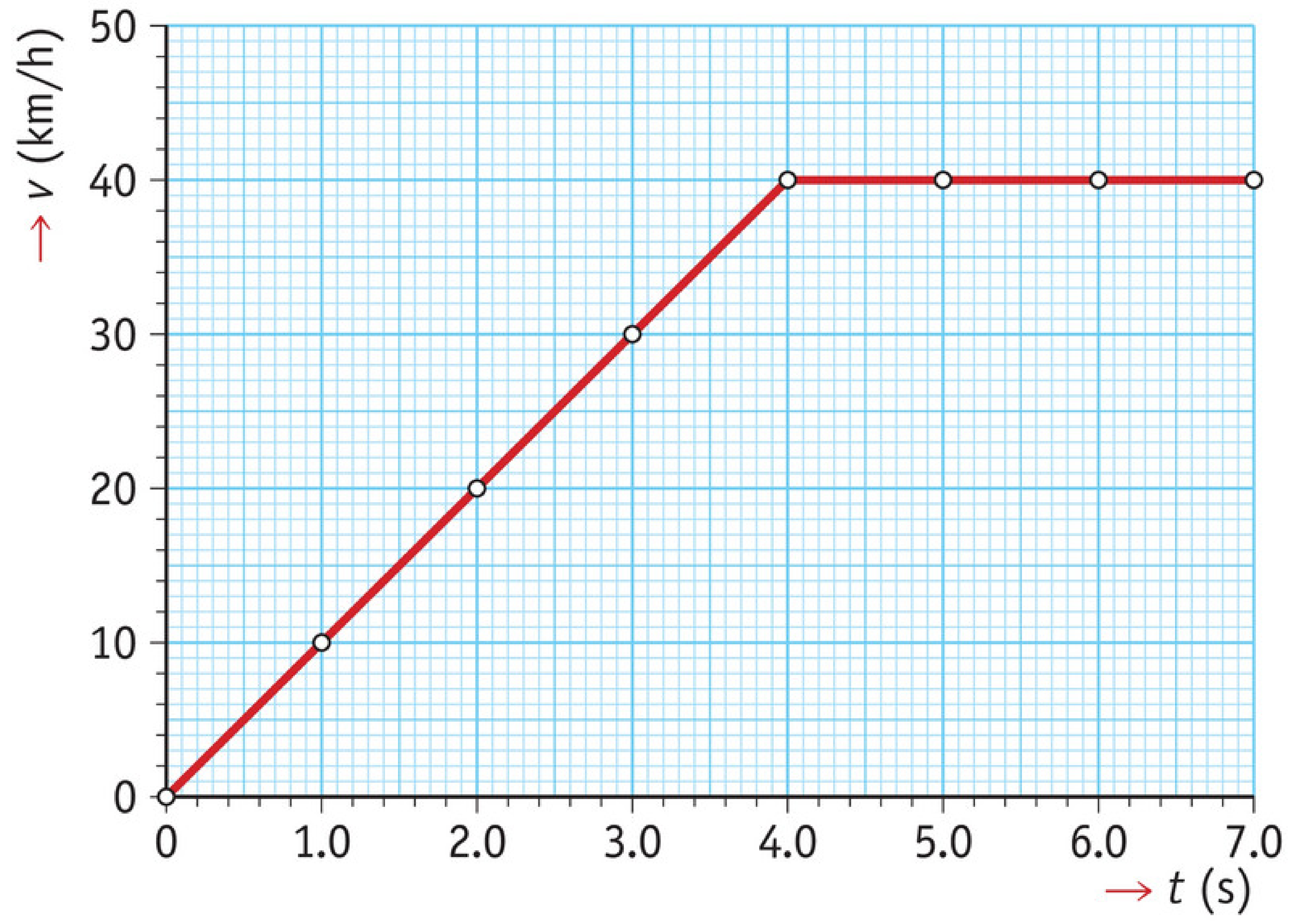


figure 2 The (*v*,*t*) diagram for a car.

The diagram shows what the speed is at any moment of the motion.

- From *t* = 0 s to *t* = 4.0 s, the motion is an **acceleration**. The car starts to move at *t* = 0 s and then speeds up gradually. This means that its speed is increasing.
- By *t* = 4.0 s, the car has reached the speed that the driver wants to go at: 40 km/h. After that, the speed of the car does not change any more. A motion during which the speed is constant is called a **uniform motion**.

You can also determine the motion in a **(displacement, time) diagram** or **(*x*,*t*) diagram**. The (*x*,*t*) diagram of the car has been drawn in figure 3. While the car is accelerating, the graph is parabolic. If the speed is constant, the graph is a slanted straight line.

Make sure that you do not confuse a (*v*,*t*) diagram (speed against time) with an (*x*,*t*) diagram (position against time). You should always look first at the variables (*x* or *v*) and units (m or m/s) that are given along the axes. You can use them to tell what type of graph it is.

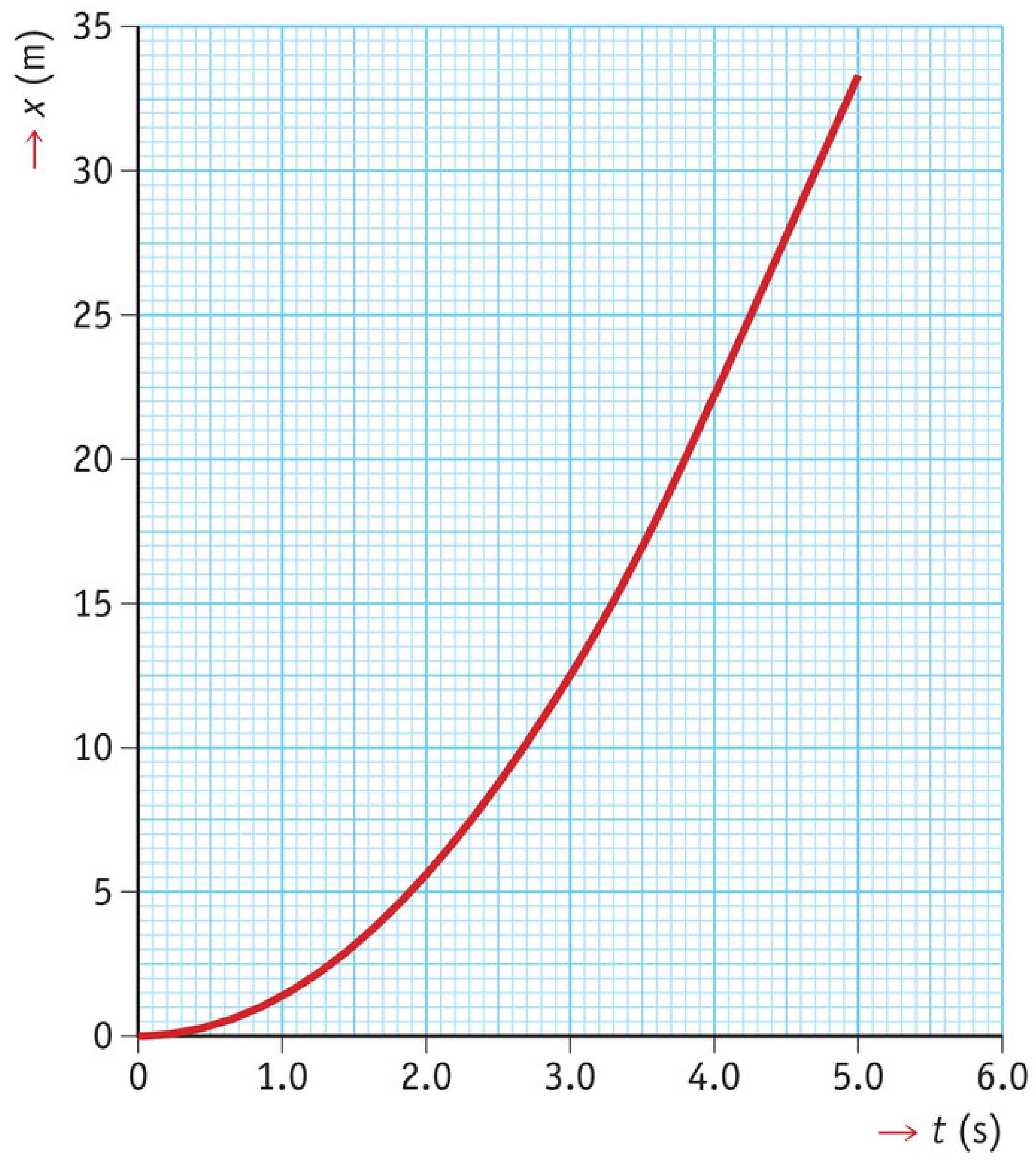


figure 3 The (*x*,*t*) diagram of the accelerating car.

UNIFORM ACCELERATION

EXP. 1

Figure 4 shows part of the (v,t) diagram in a test report on a car. You can see that the speed increases uniformly for the first four seconds: the graph is a straight line. A motion in which the speed keeps increasing at a steady rate is called a **uniform acceleration**.

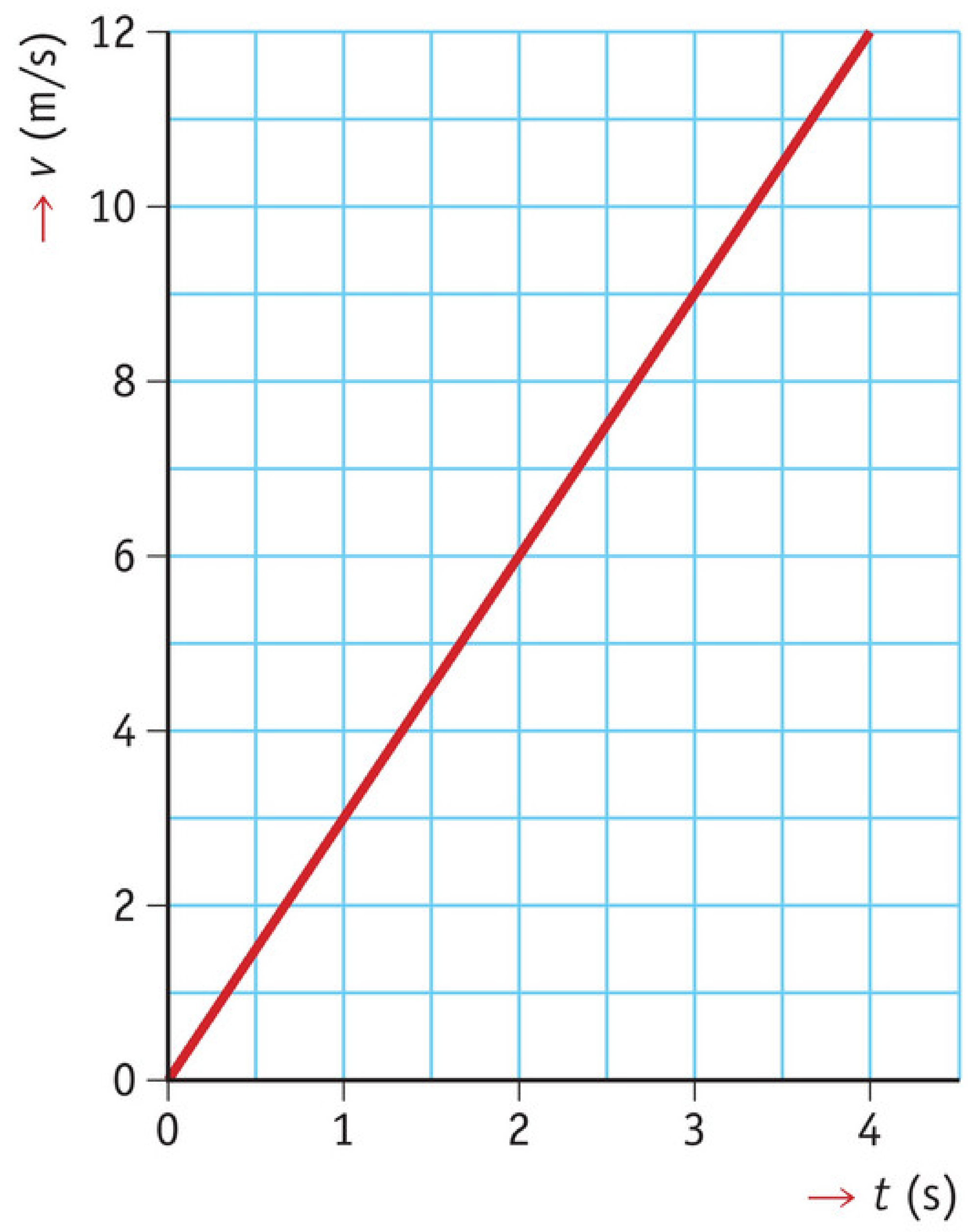


figure 4 This is how the test car accelerates as it is driven away.

The speed after one second is 3 m/s, after two seconds it is 6 m/s, after three seconds 9 m/s, and so on. In other words, the speed is increasing by 3 m/s every second. The change of speed per second is called the **acceleration**. In the motion in figure 4, the acceleration is 3 m/s per second. This is written as 3 m/s^2, and you say “three metres per second squared” or “three metres per second per second”.

The symbol for acceleration is the letter a. So this is how you write the acceleration: $a = 3\ m/s^2$. This means that the speed is increasing by 3 m/s every second.

UNIFORM DECELERATION

Figure 5 shows the (v,t) diagram for a car that is braking for a traffic light. You can see that the speed decreases evenly until the car is stationary: the motion is a **uniform deceleration**.

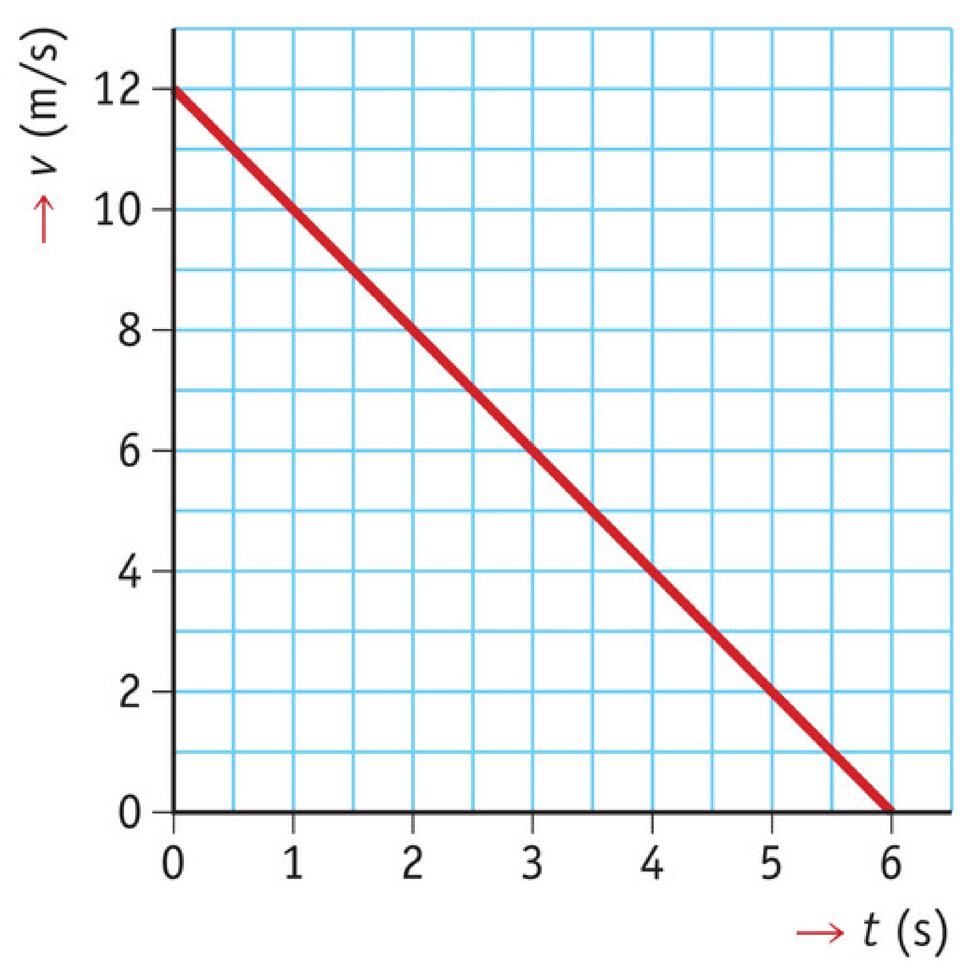


figure 5 The (v,t) diagram for a car that is braking.

The (v,t) diagram shows you that the initial speed of the car is 12 m/s. The speed after one second is 10 m/s, after two seconds it is 8 m/s, after three seconds 6 m/s, and so on. In other words, the speed is decreasing by 2 m/s every second. The reduction in speed each second is called the **deceleration**.
You then say that the deceleration is 2 m/s^2. You write $a = -2\ m/s^2$

As you can see, you use the same symbol for deceleration as for acceleration: the letter a. The only difference is that an acceleration is always a positive number and a deceleration is a negative number.

CALCULATING THE ACCELERATION

In a uniform acceleration, the speed increases uniformly from the initial speed v_i to the final speed v_f. You can calculate the change in speed Δv by subtracting the initial speed from the final speed: $\Delta v = v_f - v_i$

To calculate the acceleration, you divide the change in speed Δv by the time it took Δt. This gives you the change in speed per second:

$$a = \frac{\Delta v}{\Delta t}$$

where:

- a is the acceleration in metres per second squared (m/s^2);
- $\Delta v = v_f - v_i$ = the change in speed in metres per second (m/s);
- $\Delta t = t_f - t_i$ = the change in time in seconds (s).

EXAMPLE EXERCISE 1

A motorist wants to drive onto the motorway and pushes the accelerator right down. The car accelerates uniformly for 4.0 s. As a result, the speed increases from 60 km/h to 100 km/h.
Calculate the acceleration.

given v_i = 60 km/h = 16.7 m/s
v_f = 100 km/h = 27.8 m/s
t= 4.0 s

required a = ?

working $\Delta v = v_f - v_i = 27.8 - 16.7 = 11.1$ m/s

$$a = \frac{\Delta v}{\Delta t} = \frac{11.1}{4.0} = 2.8\ m/s^2$$

DETERMINING THE DISTANCE COVERED

When a car accelerates, it will cover a certain distance during that motion. You can determine the distance covered by looking at the (v,t) diagram of the motion. In this case, it means that you can calculate the distance using the graph.

Figure 6 shows you the (v,t) diagram of a cyclist who is moving uniformly, at a constant speed of 10 m/s. The distance that the cyclist has covered after 5.0 s can be calculated as $s = v \cdot t = 10 \times 5.0 = 50$ m. This is equal to the area under the (v,t) diagram, which is the area of rectangle ABCD.

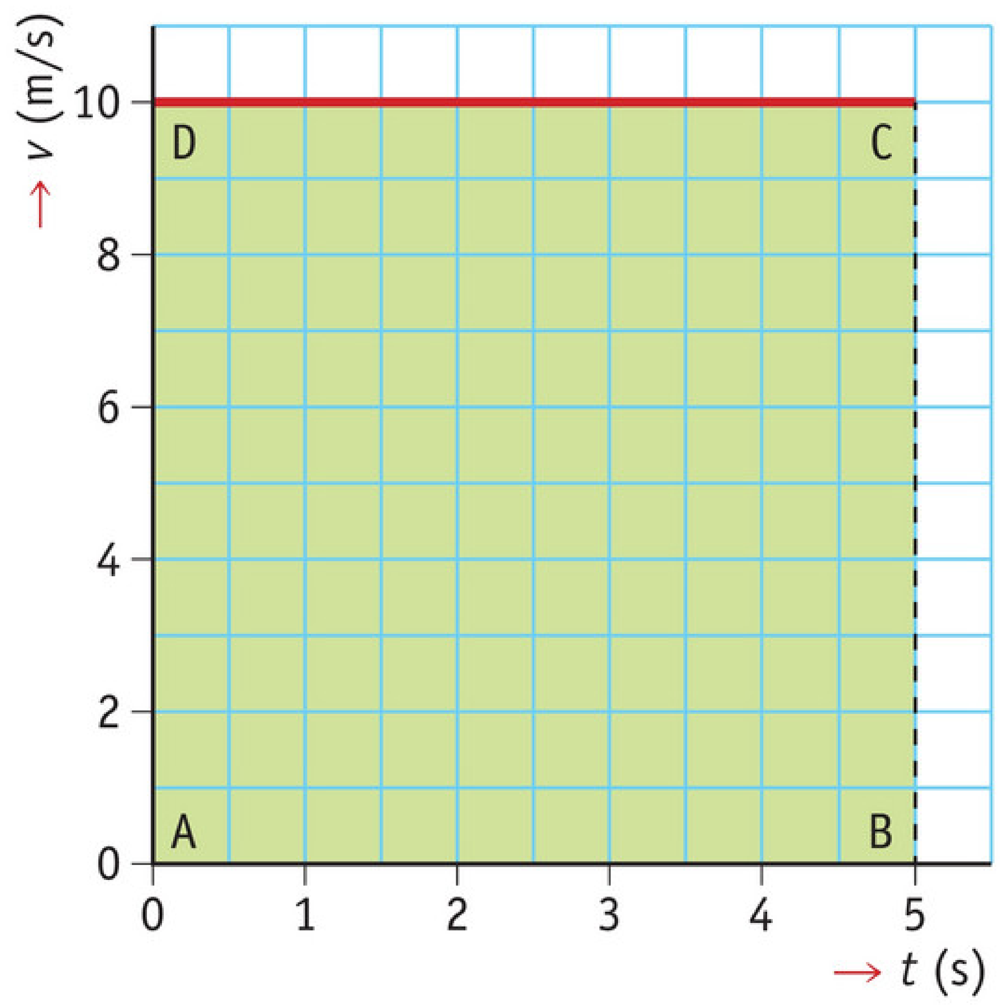


figure 6 The (v,t) diagram for a uniform motion.

You can also find the distance covered in a uniform acceleration by determining the area under the curve – which is just a straight line in this case – of the (v,t) diagram.

EXAMPLE EXERCISE 2

Figure 7 shows you the (v,t) diagram of a skier who accelerates uniformly from 36 km/h (10 m/s) to 54 km/h (15 m/s) in 5.0 s. Determine the distance that the skier covers.

given v_i = 36 km/h = 10 m/s
v_f = 54 km/h = 15 m/s
t = 5.0 s

required s = ?

working The distance covered is the area under the curve of the (v,t) diagram:
s = area of rectangle ABCD + area of triangle DCE
= 5 × 10 + ½ × 5 × (15 − 10) = 62.5 m; or 63 m when rounded off

So the skier covers a distance of 63 m.

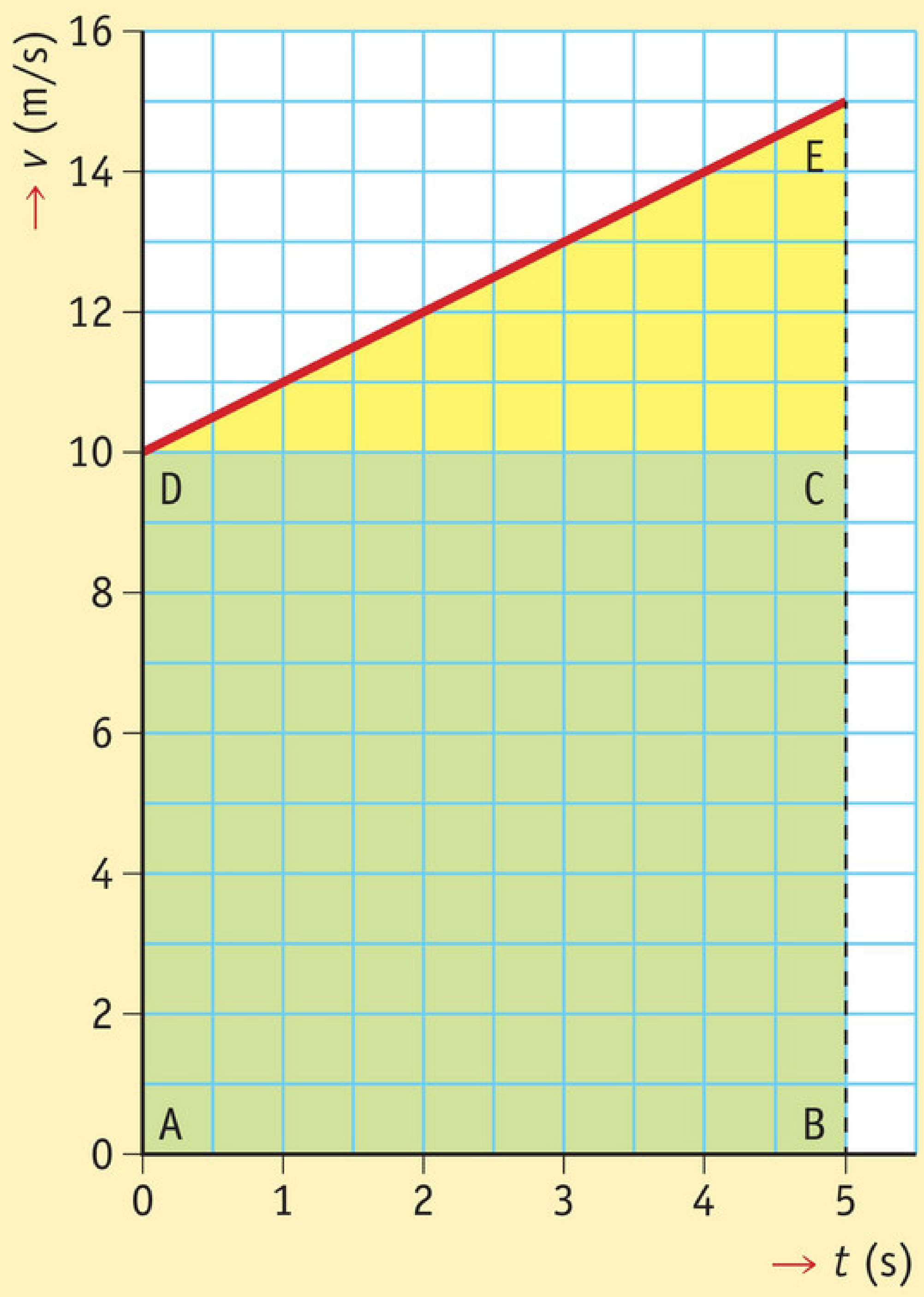


figure 7 The (v,t) diagram for an accelerating motion.

PLUS NON-UNIFORM ACCELERATION

In daily life, you will never experience a motion like in figure 2. An accelerating car will not have the same acceleration all the time. The motion will not change abruptly from an acceleration to a uniform motion either.

Figure 8 shows you a more realistic (v,t) diagram for a racing car. As the speed increases, the graph becomes less and less steep. The speed increases by less and less and so the acceleration of the car is becoming smaller. The area under the graph no longer consists of shapes that you can easily determine the area of such as rectangles and triangles. It is then difficult to accurately determine the distance covered using the (v,t) diagram.

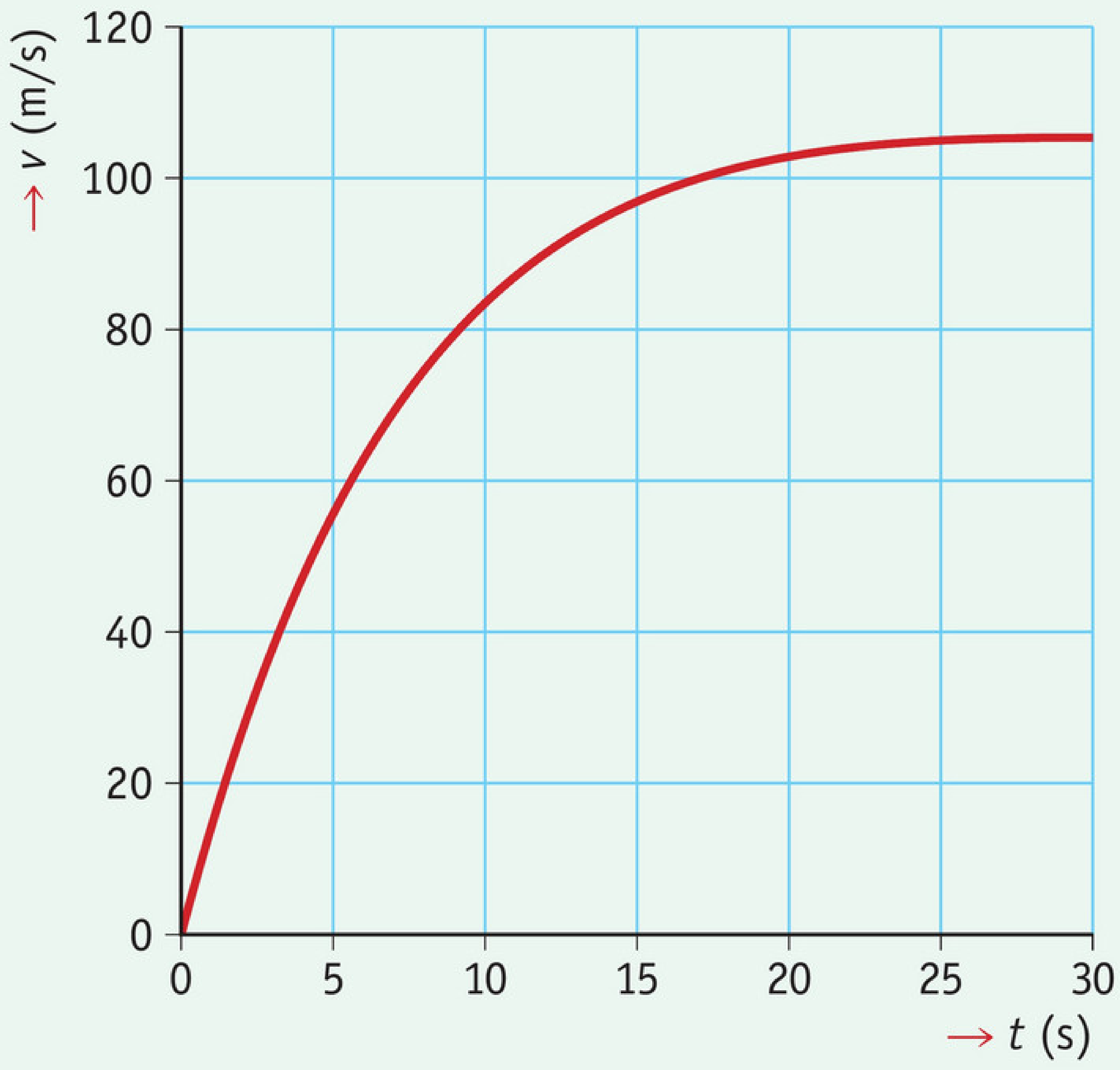


figure 8 The (speed, time) diagram of an accelerating Formula 1 racing car.

A quick way to estimate the distance covered is shown in figure 9. For example, if you want to determine the displacement between the time t = 0 s and t = 30 s, you first determine the displacement that corresponds to the area of a single square. Then you count the number of squares under the graph. As you can see in figure 9, you try to estimate the number of squares that are only partly under the graph as accurately as possible. In this case:

- The number of squares under the line is (about) 25.
- The area of one square is equal to 20 m/s × 5.0 s = 100 m.
- So the displacement is 25 × 100 m = $2.5 \cdot 10^3$ m.

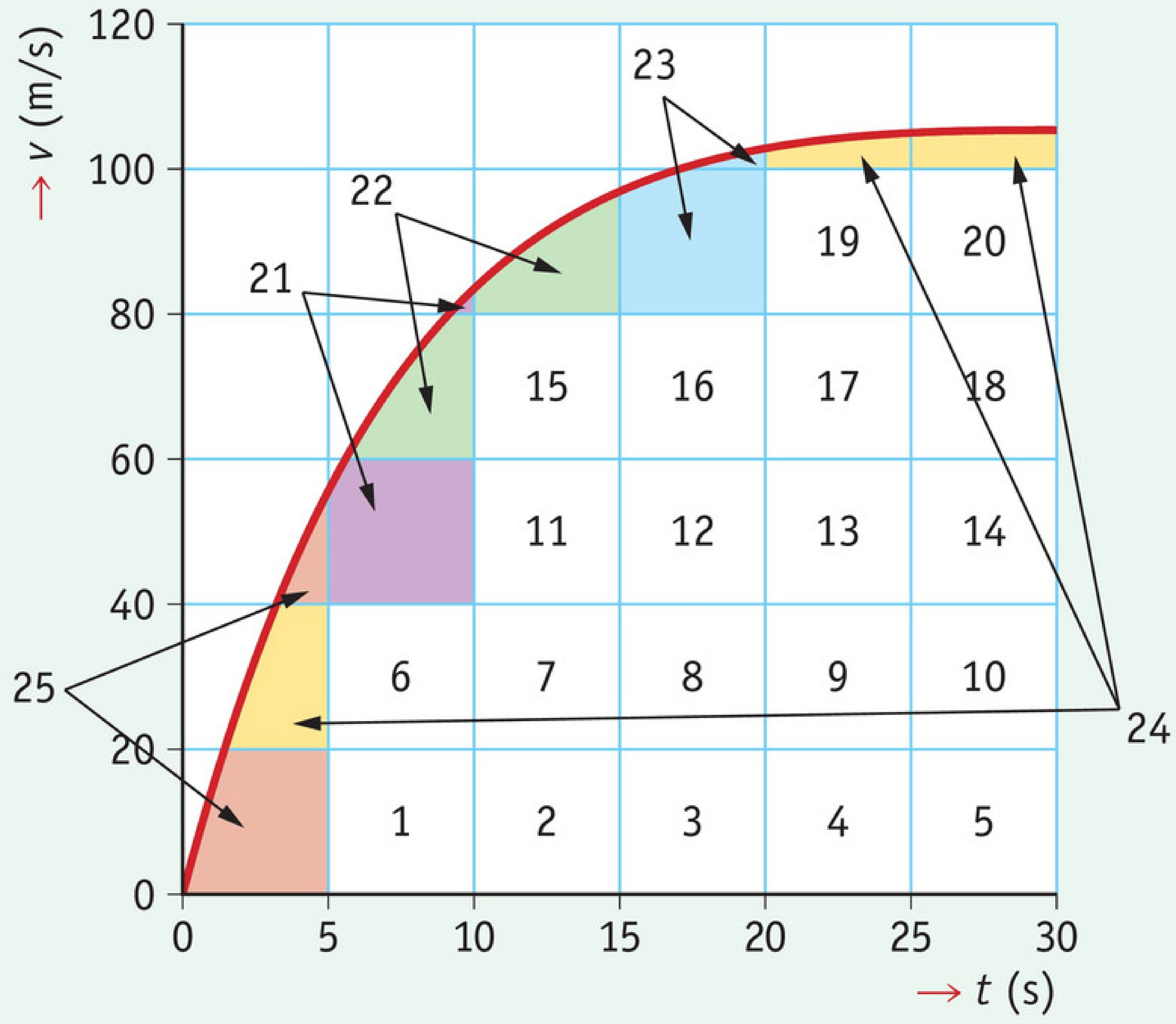


figure 9 This is how you count the squares under a curved graph.

Practice the concepts using the *Flash cards*.

COURSE MATERIAL

1

Answer the following questions.

a What do you call a motion:
- where the speed is increasing uniformly?
- where the speed stays the same all the time?

b What formula can you use to calculate the acceleration of a moving object?

c What is meant by the statement that the acceleration of the object is 2.5 m/s^2?

d How can you determine the distance covered using the (v,t) diagram of a motion?

2

Fill in the rest of table 1.

table 1 Various variables and their units.

variable	symbol	unit	symbol
distance			m
		second	
			m/s
	a		

IN PRACTICE

3

Sketch the (v,t) diagram of:

a a speed-skater who does a 40 s lap on the skating rink at a constant speed of 36 km/h (figure 10).

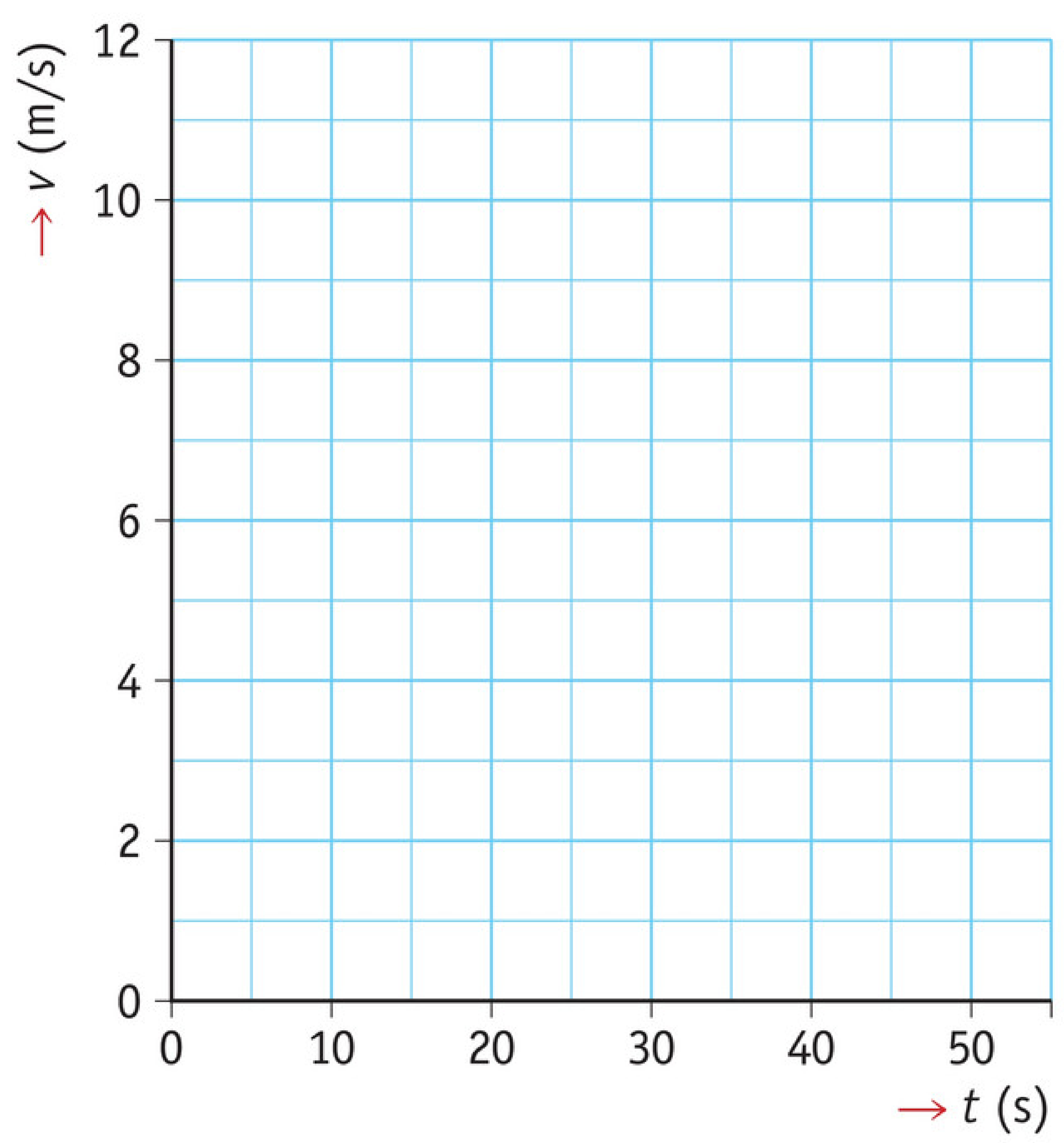


figure 10 The (v,t) diagram of a speed-skater.

b a ski-jumper who goes down a ski jump under a uniform acceleration. When he jumps from the ramp after 12 s, his speed is 90 km/h (figure 11).

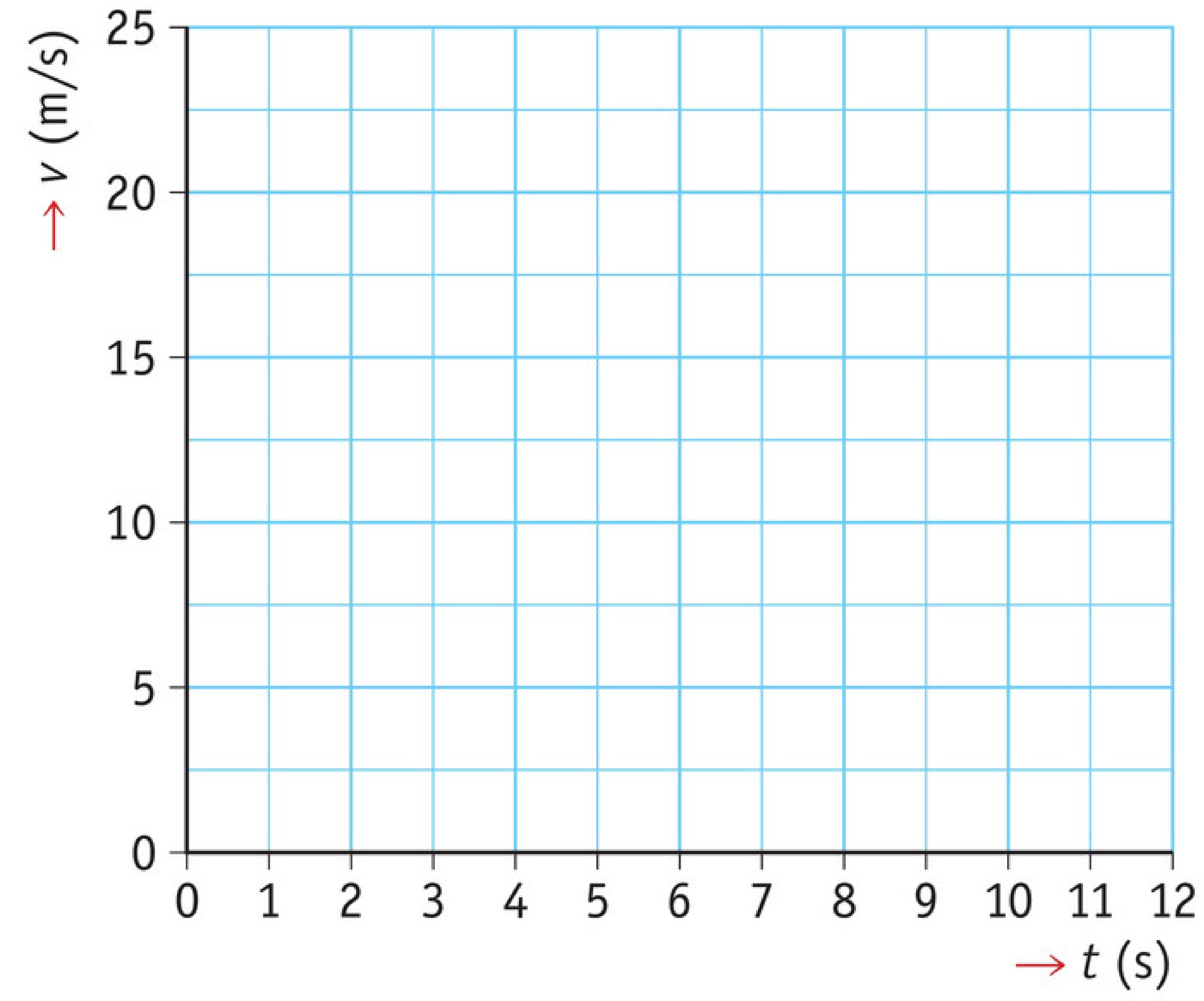


figure 11 The (v,t) diagram of a ski-jumper.

c a car driver who accelerates from 63 to 81 km/h in 3.0 s during an overtaking manoeuvre (figure 12).

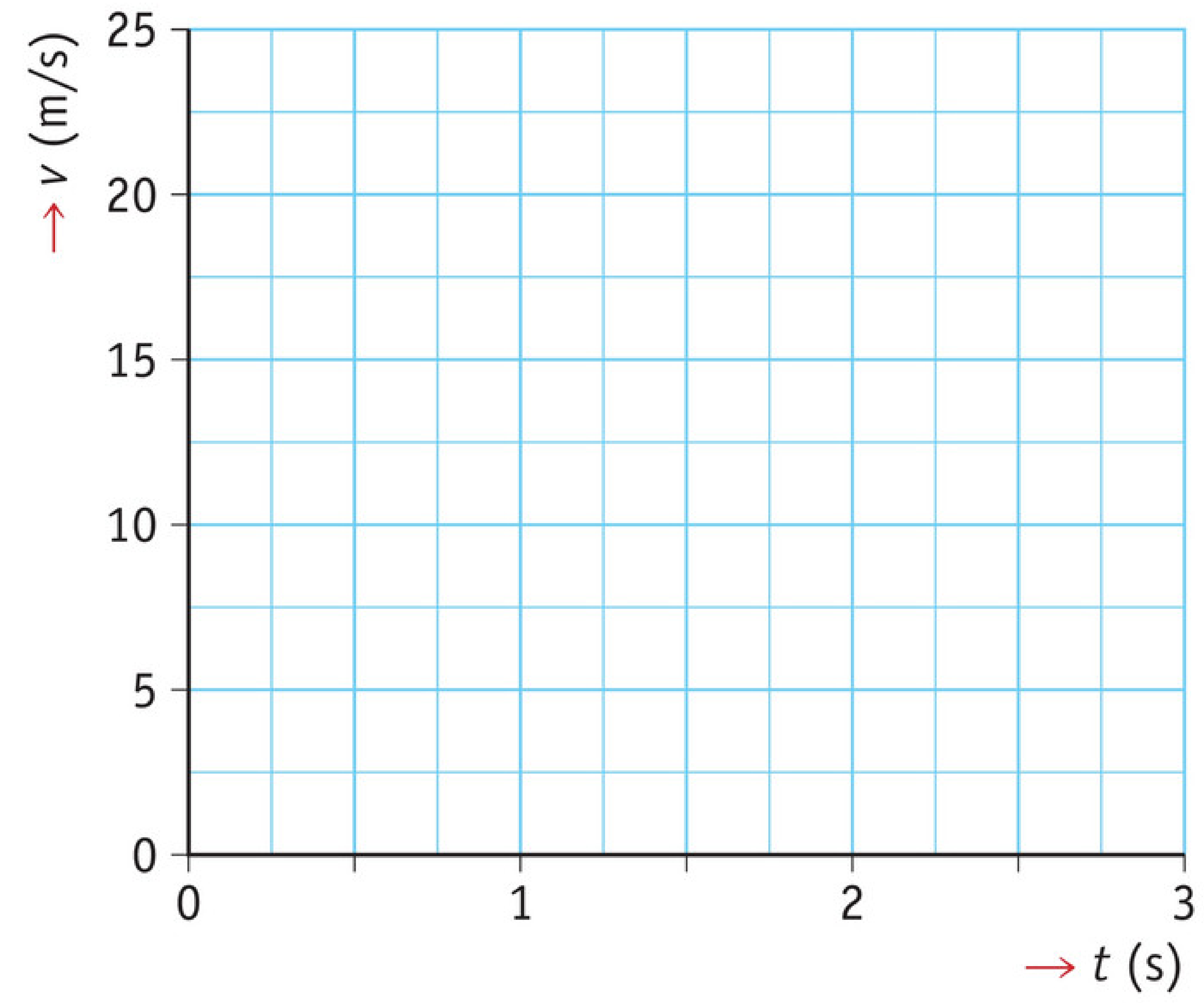


figure 12 The (v,t) diagrams of a car driver.

4 Figure 13 shows you the (v,t) diagram for Wendy on her moped.

a Determine Wendy's acceleration during the first 2.0 s.

b Determine the distance that Wendy covers in the first 8.0 s of her journey.

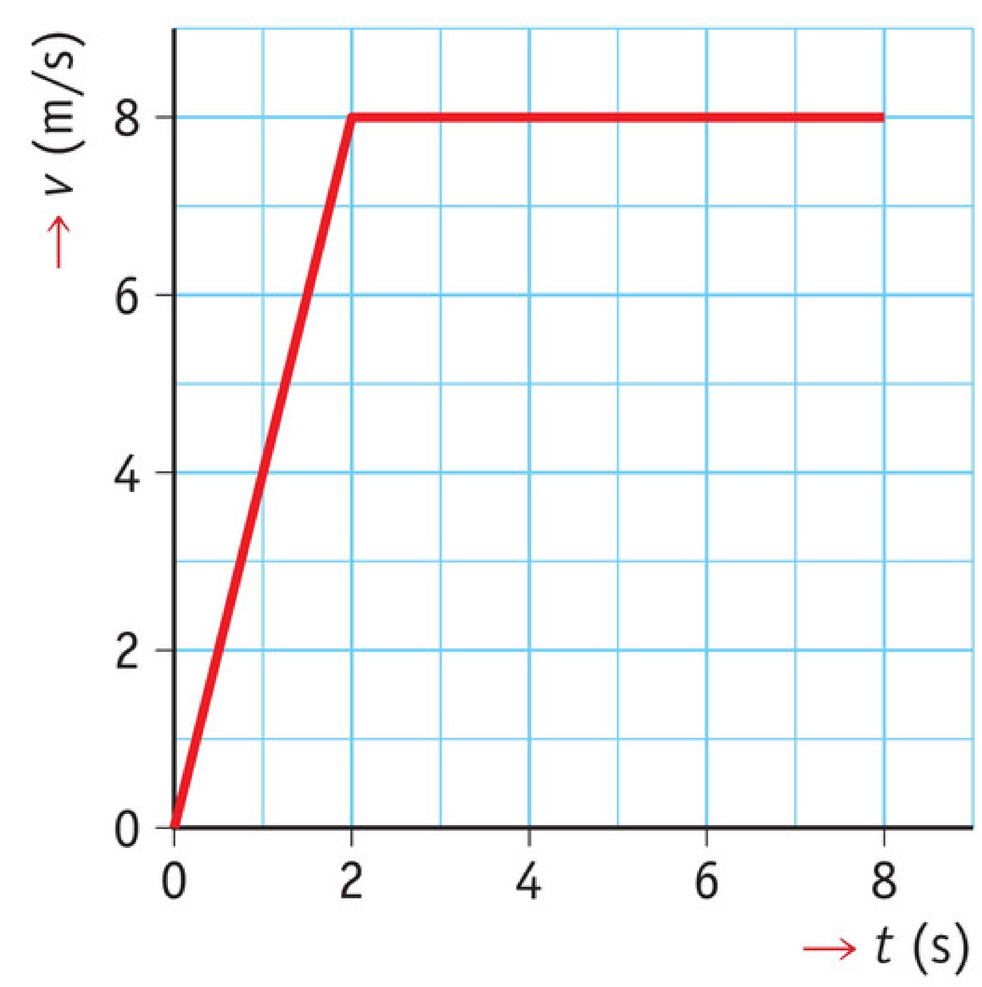


figure 13 Wendy's' (v,t) diagram.

5 A car is going at a speed of 63 km/h. The car driver gives more gas so that the speed increases to 90 km/h in 5.0 s.

a Calculate the car's acceleration in m/s^2.

b Determine the distance that the car covers during the motion. To do this, first sketch the (v,t) diagram in figure 14.

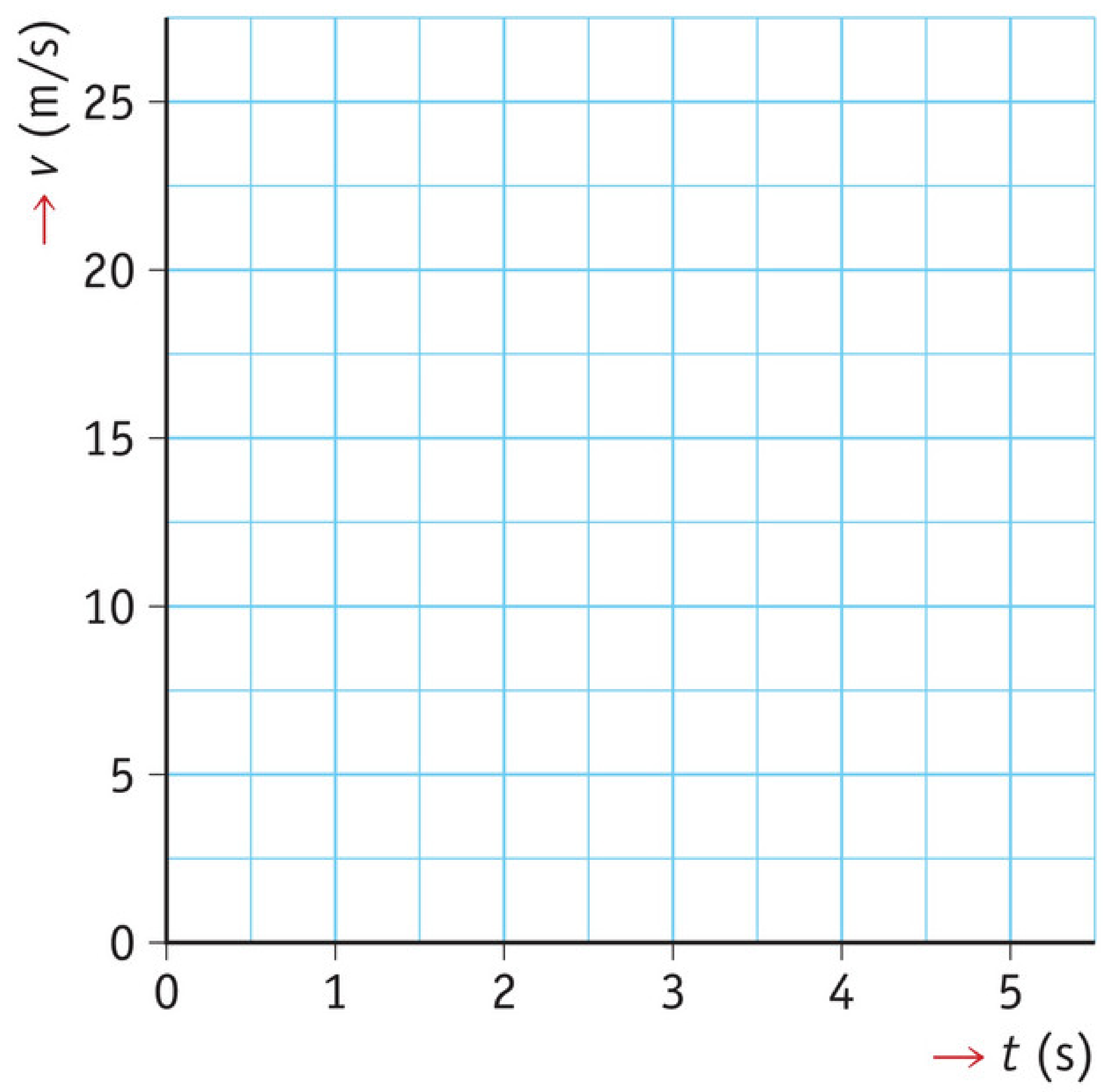


figure 14 The (v,t) diagram of an accelerating car.

c Determine what the final speed would have been if the car had accelerated for 6.0 s instead of 5.0 s. Give your answer in km/h.

★ 6 In Example Exercise 2 about the accelerating skier, the distance covered was determined using a graph. You can also calculate the distance using the formula $s = v_{avg} \cdot t$. Show that this method gives the same answer.

7 Read the newspaper article in figure 15.

a Calculate the top speed of the cheetah in km/h.

b Explain how many strides the cheetah needs (at least) to achieve a top speed of 27 m/s.

c Measurements showed that one stride of a cheetah takes 0.45 s. Calculate the cheetah's acceleration.

Acceleration, not speed, is what makes a cheetah a great hunter



The cheetah rarely reaches the top speed (27 m/s) for which it is famous. However, the animal has fantastic acceleration and is extremely manoeuvrable. British scientists measured the speed of cheetahs in the wild and found an average top speed of 'only' 14.9 m/s. In comparison: a top human sprinter reaches 12 m/s.
The animals have another great advantage during the hunt: their muscles can contract extremely quickly. In a single stride, they can accelerate by 3 m/s or decelerate by 4 m/s. They always decelerate just before changing direction: this lets them corner much more sharply.

figure 15 Wild cheetahs with collars that measure their acceleration.

8 Figure 16 gives the (x,t) diagram for a sprinter in a race. The starting pistol is fired at time $t = 0$.

a Explain why the line goes horizontally for a while after $t = 0$.

b Explain whether the average speed in part B is higher or lower than the average speed in part C, or exactly the same.

c When the sprinter starts to move, he has a constant acceleration of 4.0 m/s^2 for the first 2.0 s.
Calculate the speed after those 2.0 s.

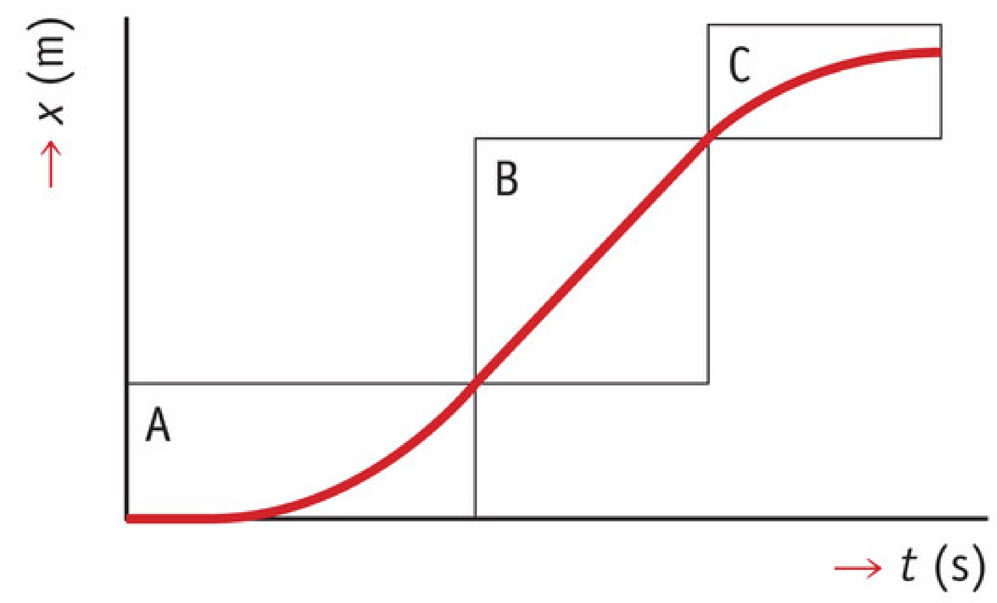


figure 16 The (x,t) diagram of a sprinter.

9 You can derive an (x,t) diagram from a (v,t) diagram and vice versa. There are four (x,t) diagrams on the left of figure 17 and four (v,t) diagrams on the right.
Which diagrams belong together and why?

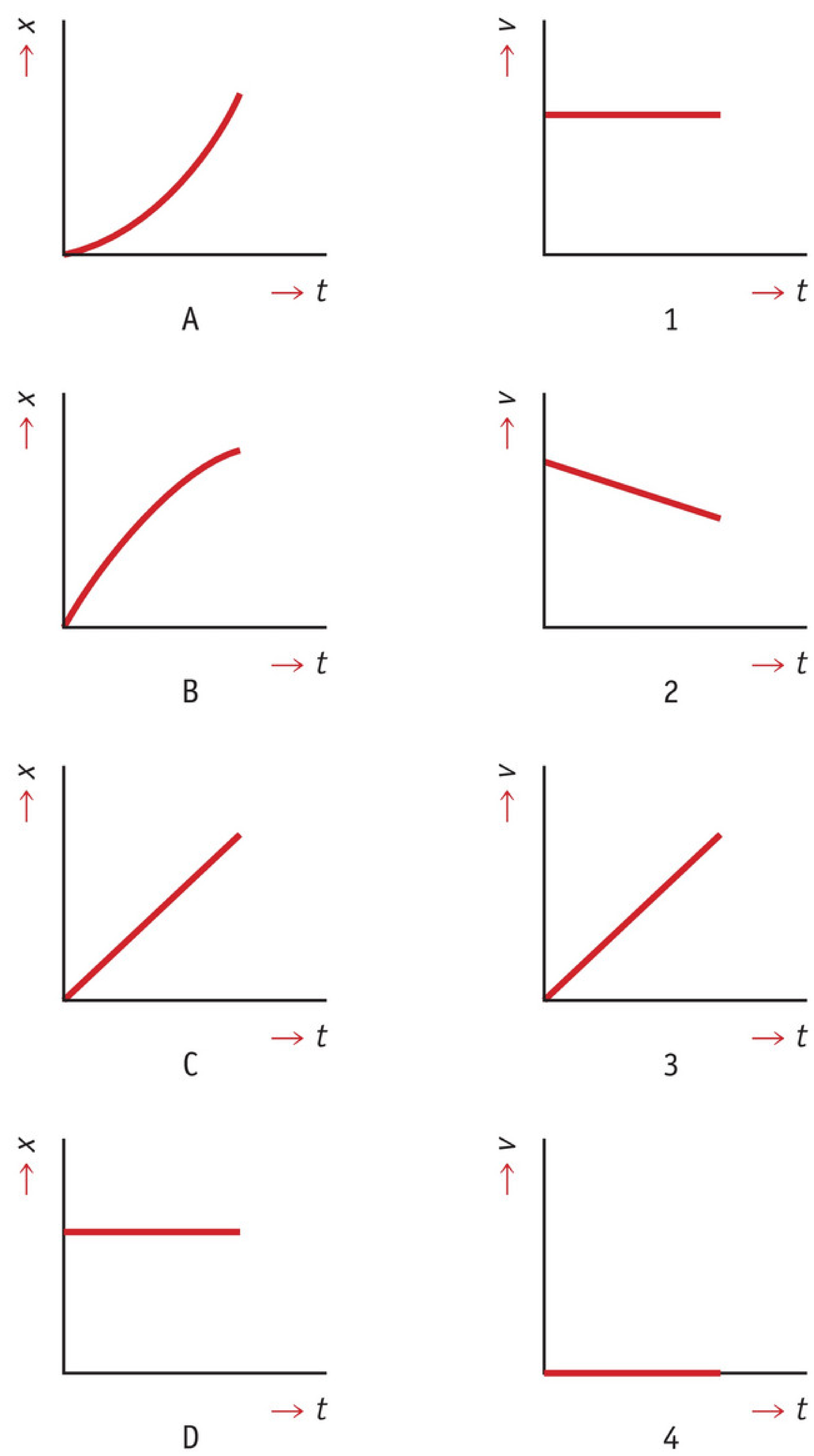


figure 17 Which diagrams belong together?

Test what you know with *Test yourself.*

PLUS NON-UNIFORM ACCELERATION

10 In 2009, a team of American students set the speed record for an electric car. Their *Buckeye Bullet* achieved about 500 km/h on a salt flat in the state of Utah. The car was very low and extremely well streamlined. Figure 18 shows the (v,t) diagram of the record run.

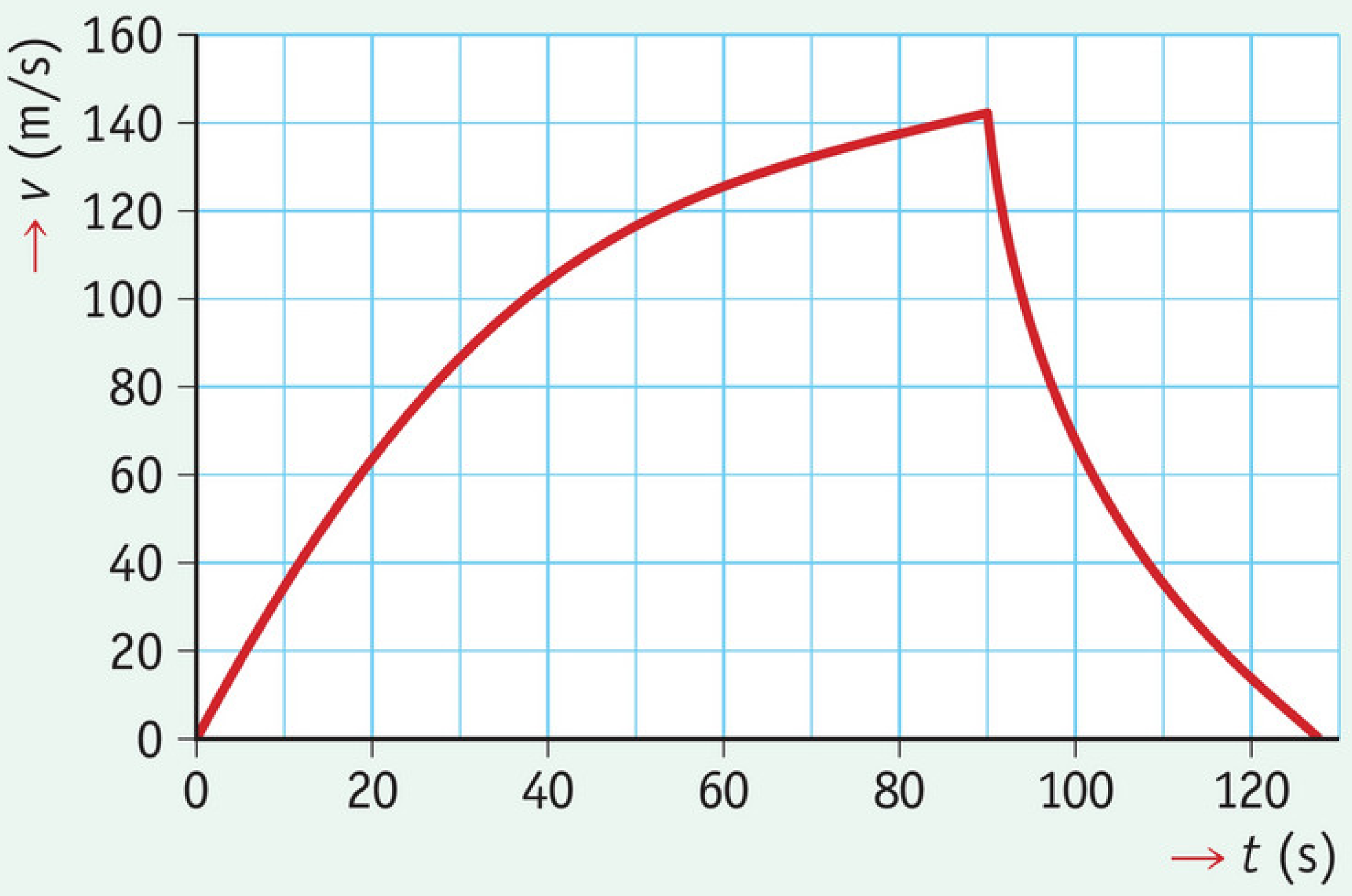


figure 18 The (v,t) diagram of the record ride of the *Buckeye Bullet*.

a You can divide the motion into three periods.
What type of motion was the car doing in each of the three periods?

b How can you explain why the acceleration in the first part was almost constant but no longer in the second period?

c Use figure 18 to explain whether the braking distance of the *Buckeye Bullet* is greater than / equal to / less than the distance needed to reach full speed.

d Determine how many kilometres the car covers until it reaches full speed.

e Calculate the average speed between time t = 0 s and the time at which the car reaches its top speed.

11 Figure 19 shows the (v,t) diagram of an aircraft that has to make an emergency landing on the landing strip.

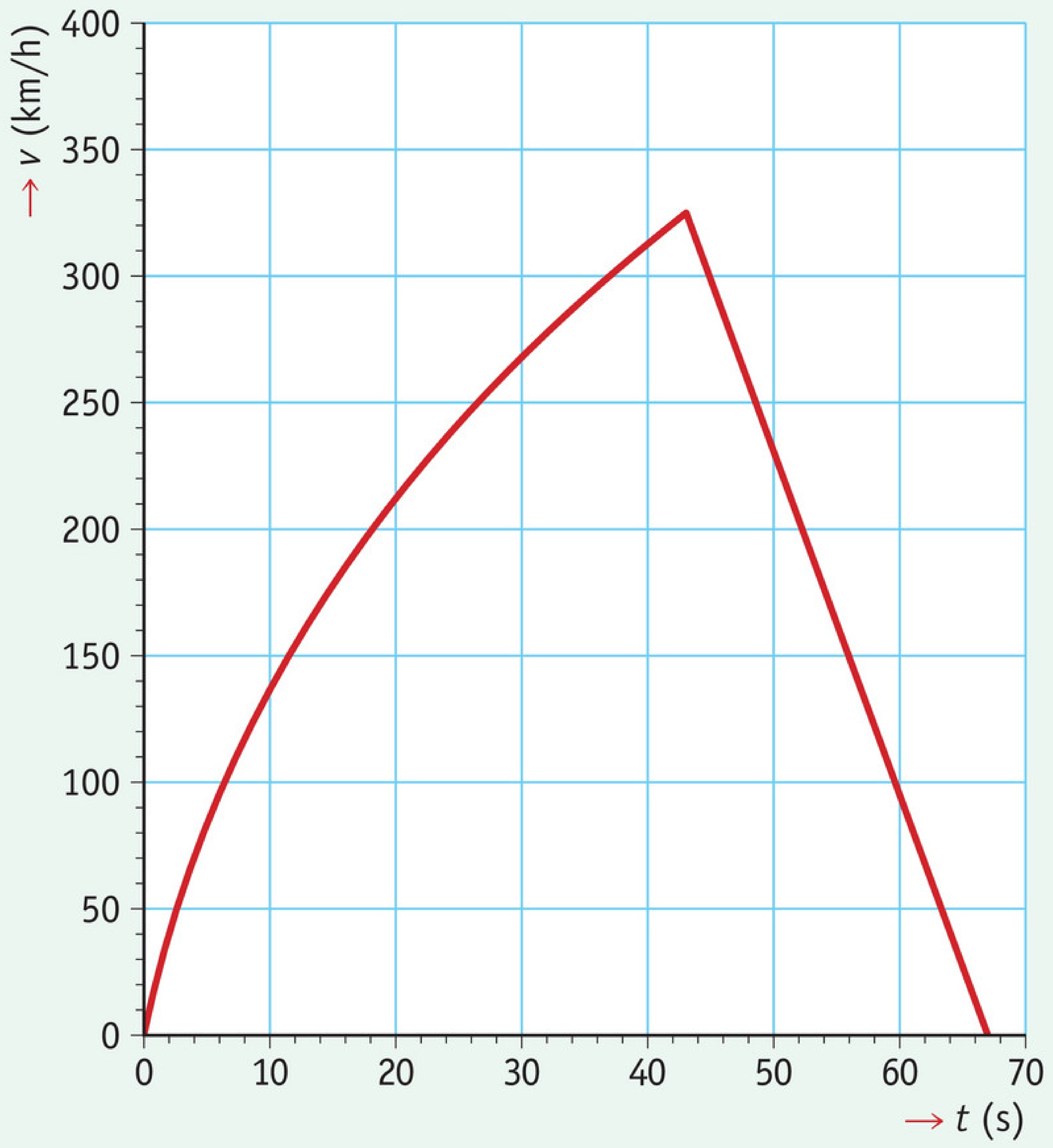


figure 19 The (v,t) diagram of the motion of the aircraft.

a Show that the area of one square equals a displacement of $1.39 \cdot 10^2$ m.

b Determine the average speed of the aircraft during this motion.

2 Force, mass and acceleration

LEARNING OBJECTIVES

4.2.1 You can explain the relationship between the mass and inertia of an object.
4.2.2 You can explain the relationship between the resultant force, the mass and the acceleration.
4.2.3 You can do calculations involving Newton's Second Law, $F = m \cdot a$
4.2.4 You can explain that the acceleration due to gravity for all objects in free fall is the same.
PLUS 4.2.5 In a fall where the air resistance is not neglected, you can explain the relationship between force and motion and you can explain it using calculations.

When a truck is heavily loaded, it can only get going slowly. The greater the mass of the load, the smaller the acceleration if the driver still gives the same amount of gas. You will notice the same effect if you try to cycle with someone sitting on the back of your bike: it takes much longer to accelerate.

INERTIA

The mass not only affects the acceleration that makes an object pick up speed but also determines how difficult it is to brake the object or make it change direction. The greater the mass of an object, the harder it is for you to change the speed or the direction of motion. That's why a driver has to be extra careful if his truck is heavily loaded.

An object with a large mass has a lot of **inertia**. A large resultant force is needed in order to have any noticeable effect on the speed or the direction of motion. A driver who is transporting steel girders knows that his load has a great deal of inertia. He therefore makes sure that the girders are fixed firmly in place. Otherwise they might continue moving forwards in an emergency stop, even though the truck comes to a standstill (figure 1).

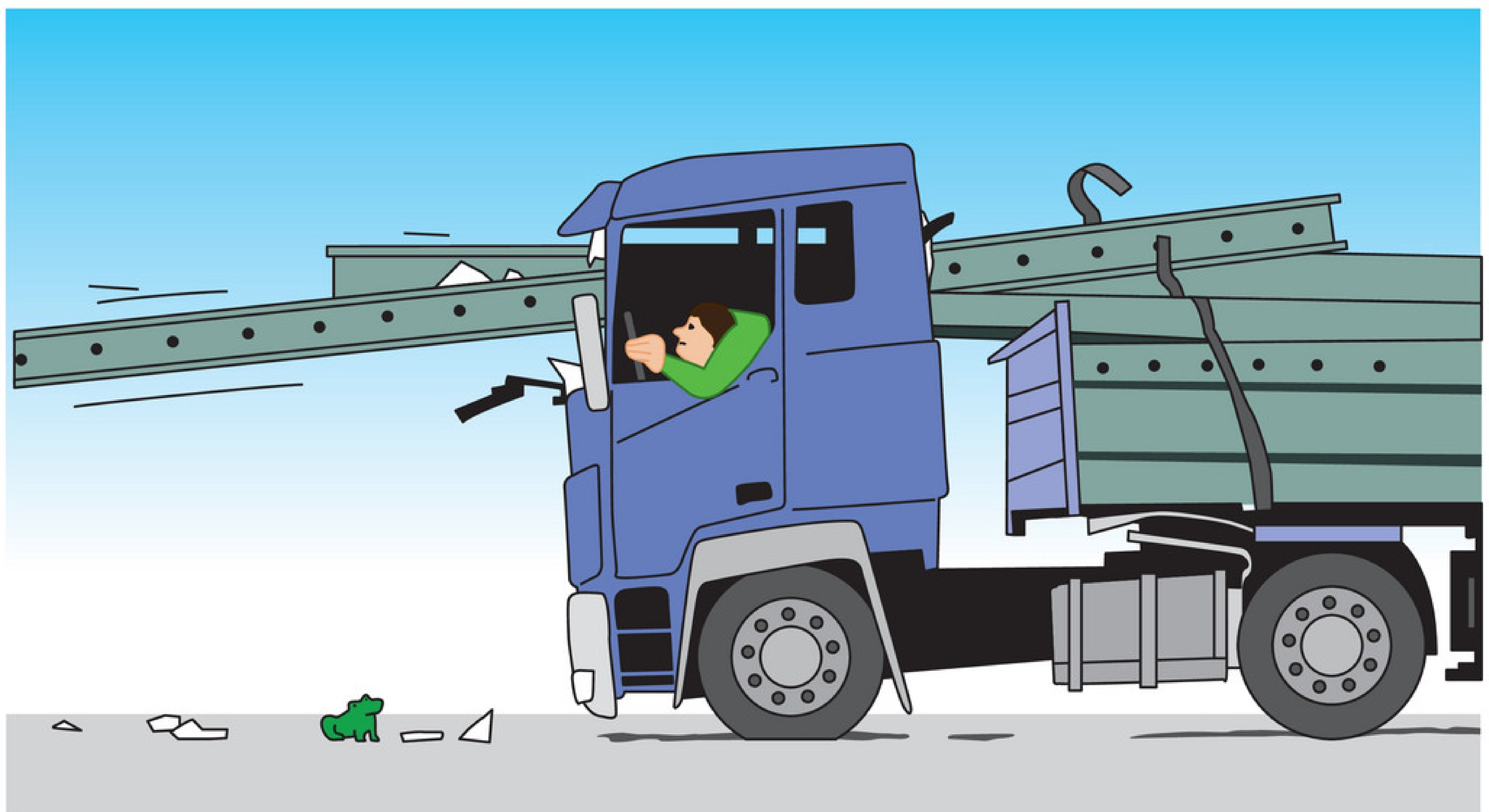


figure 1 Steel girders have a large mass and therefore also a lot of inertia.

NEWTON'S SECOND LAW

EXP. 2+3

The setup shown in figure 2 lets you accelerate a trolley along an air cushion track. The track has a large number of holes that air is flowing out of. Because the trolley is then 'floating' on a layer of air, the resistance forces are negligible. The resultant *F* is then equal to the force of gravity on the weight carrier and the weight. The mass *m* of the trolley and the weight can be determined using scales and the acceleration *a* by measuring the change in speed using a motion sensor.

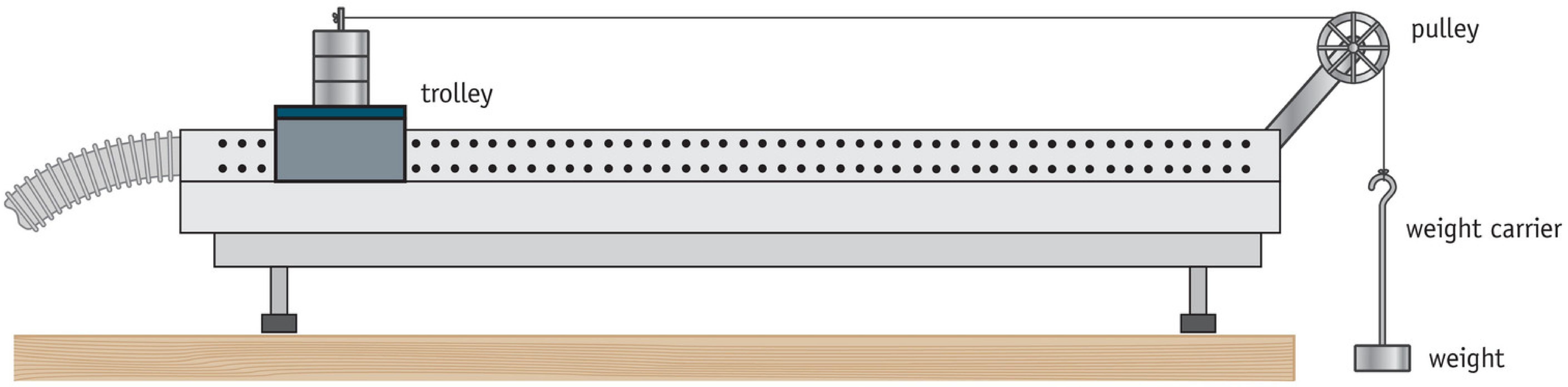


figure 2 An experiment with an air cushion track.

Tests like these show that there is a simple relationship between the resultant, the mass and the acceleration. Expressed as a formula:

$$F_{res} = m \cdot a$$

where:

- F_{res} is the resultant force in newtons (N);
- m is the mass in kilograms (kg);
- a is the acceleration in metres per second squared (m/s^2).

This formula is also known as **Newton's Second Law**.

The definition of the newton, the unit of force, is based on the formula $F = m \cdot a$. According to the definition, 1 N equals the resultant force when a mass of 1 kg is accelerated by 1 m/s^2.

EXAMPLE EXERCISE 1

A car accelerates in 4.0 s at a constant acceleration from 0 km/h to 54 km/h. The mass of the car is 800 kg.
Calculate the size of the resultant force that is accelerating the car.

given $v_i = 0$ m/s
$v_f = 54$ km/h $= 15$ m/s
$\Delta t = 4.0$ s
$m = 800$ kg

required $F_{res} = ?$

working $\Delta v = v_f - v_i = 15$ m/s

$$a = \frac{\Delta v}{\Delta t} = \frac{15}{4.0} = 3.75 \text{ m/s}^2$$

$$F_{res} = m \cdot a = 800 \times 3.75 = 3000 \text{ N} = 3.0 \text{ kN}$$

The resultant is therefore 3.0 kN. The driving force applied to the car is greater: there are also resistance forces that have to be overcome, of course.

CALCULATING THE ACCELERATION

A motorbike can generally accelerate much faster than a family car. This is because the mass of a motorbike is much less. So if the resultant acting on both vehicles is equally large, the motorbike is accelerated much more quickly. You can also work that out from the formula $F_{res} = m \cdot a$. If the resultant F_{res} is equally large, but the mass m is much smaller, the acceleration a must be much larger.

EXAMPLE EXERCISE 2

Figure 3 shows you a car and a motorbike next to each other. The mass of the car (including the driver) is 900 kg and the mass of the bike is 300 kg. When the main road is clear, the car and the motorbike both accelerate away. The resultant acting on both vehicles is 1.8 kN.
Calculate the accelerations of both vehicles.

	car:	*motorbike:*
given	$F = 1.8$ kN	$F = 1.8$ kN
	$m = 900$ kg	$m = 300$ kg
required	$a = ?$	$a = ?$
working	$a = \frac{F}{m} = \frac{1800}{900} = 2.0 \text{ m/s}^2$	$a = \frac{F}{m} = \frac{1800}{300} = 6.0 \text{ m/s}^2$



figure 3 A motorbike can generally accelerate much faster than a car.

CALCULATING THE BRAKING FORCE

The formula $F_{res} = m \cdot a$ lets you calculate the resultant on a braking vehicle. In this case, the letter a stands for the braking deceleration (the reduction in speed each second). The letter F stands for the resultant, as always. In this case, the resultant is the total braking force that is exerted on the vehicle.

EXAMPLE EXERCISE 3

A car has a mass of 1300 kg. The brakes must be able to provide enough braking force for a deceleration of at least 5.2 m/s² (figure 4).
Calculate the minimum braking force required.

given $m = 1300$ kg
$a = -5.2$ m/s²

required $F_{res} = ?$

working $F_{res} = m \cdot a = 1300 \times 5.2 = -6760 \text{ N} = -6.8 \text{ kN}$

You say that the braking force (after rounding) is 6.8 kN, but you should write $F_{res} = -6.8$ kN. The minus sign shows that the braking force is acting in the opposite direction to the direction of motion.

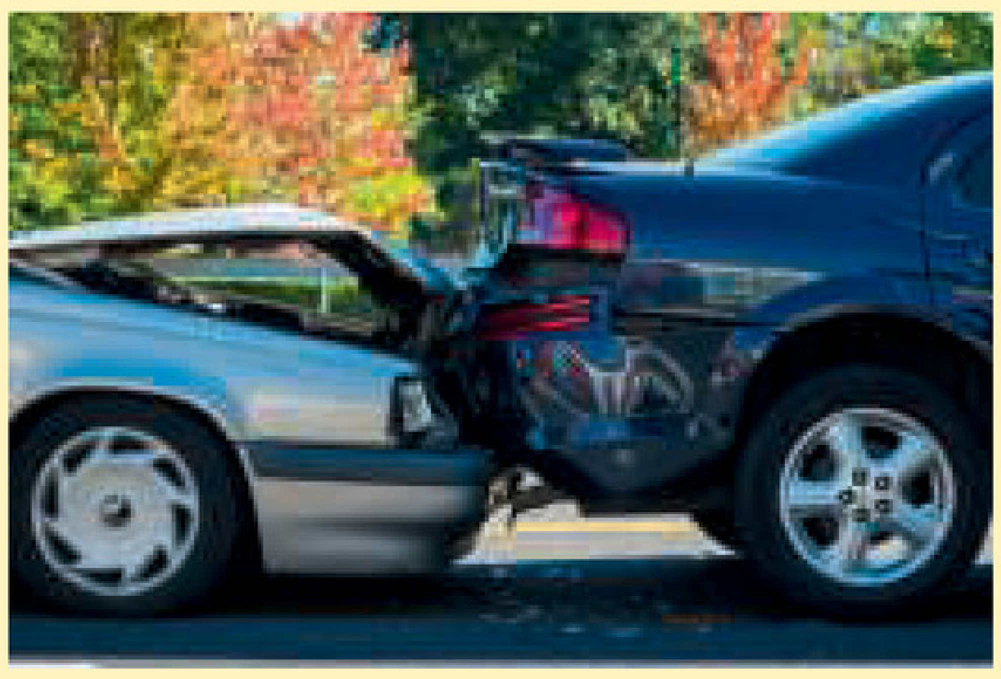


figure 4 in this situation, the braking force was insufficient.

THE ACCELERATION DUE TO GRAVITY

Figure 5 shows you a stroboscopic photo of a falling ping-pong ball. The distances between two successive images are increasing. This tells you that the ball is accelerating. You can also carry out this experiment in a tube with the air pumped out (a vacuum). In that case, the only force acting on the ball is gravity. It then moves in **free fall**.

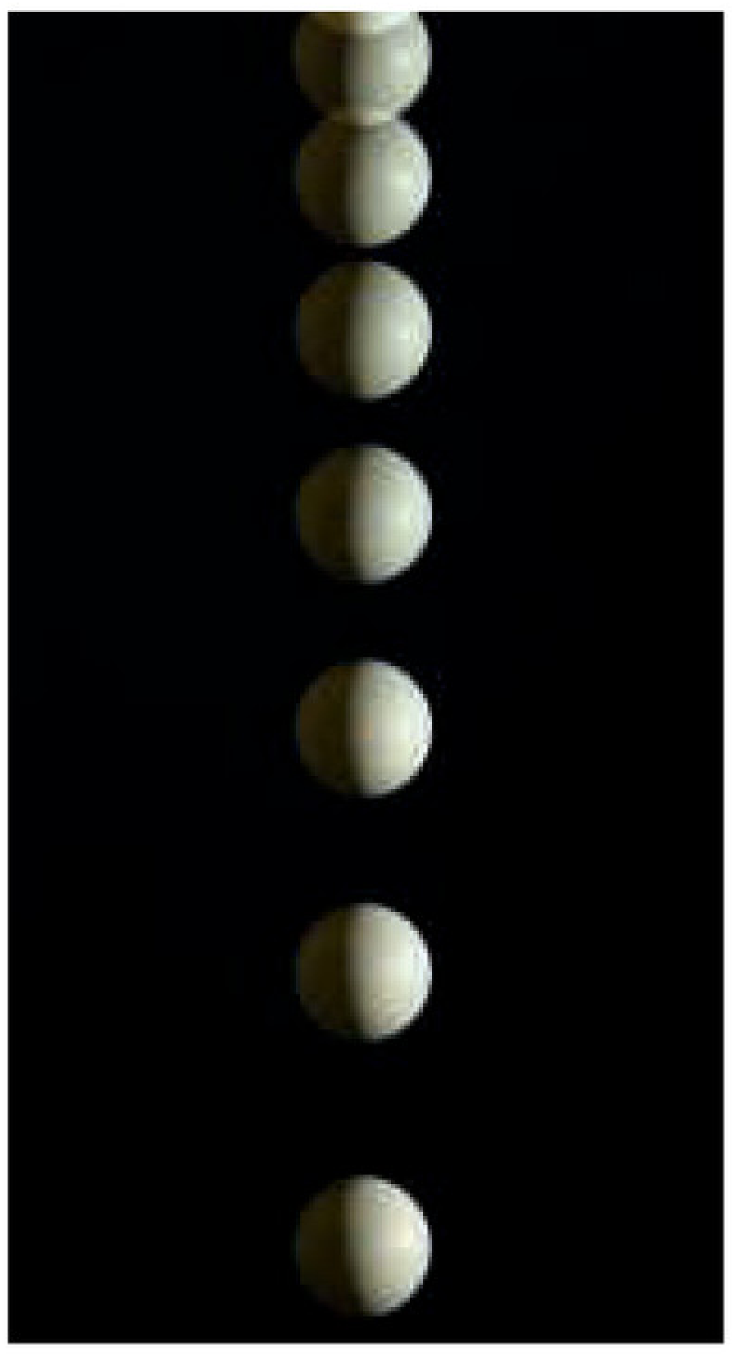


figure 5 A ping-pong ball under a downward acceleration.

For an object in free fall, the resultant F_{res} is equal to the force of gravity, so $F_{res} = F_g$. There are no other forces acting on the object. The force of gravity is not only $F_g = m \cdot g$, but also $F_g = F_{res} = m \cdot a$

When you combine these two formulae, you get $m \cdot a = m \cdot g$ and after dividing both sides by m, you get $a = g$

The **acceleration due to gravity** a in free fall is always equal to g. In experiments on Earth, the acceleration due to gravity in free fall is always (rounded off) 9.8 m/s², no matter what the object is. To emphasise this, the symbol g is used for the acceleration due to gravity instead of a. The letter g therefore gets used for two variables: the force due to gravity (in N/kg) and the acceleration due to gravity (in m/s²).

PLUS FALLING IN AIR

A falling motion in air is completely different from a falling motion in a vacuum. You can see that for instance in a parachute jump. Two forces act on a parachutist who jumps out of an aircraft: gravity and air resistance. Gravity always stays the same, but air resistance changes: the faster the parachutist falls, the greater it becomes.

The air resistance is proportional to the square of the speed. If the fall speed doubles, the air resistance becomes 4× greater. The parachutist can increase their air resistance further by spreading out their arms and legs. This increases their frontal cross-section. That is the surface area of the parachutist that you would see if you photographed them from below when they are falling straight at you.

At first, the parachutist accelerates. But because their speed keeps increasing, the air resistance also increases quickly. A balance is reached after just a few seconds: gravity and air resistance balance each other out. From that moment on, the parachutist falls at a steady speed of about 120 km/h (figure 6a).

When the parachute opens, the total air resistance suddenly becomes much greater. The frontal cross-section increases a great deal all at once. The parachutist decelerates as a result. The speed – and therefore also the air resistance – decreases until a new balance is reached. From that moment on, the parachutist floats down to the ground at a steady speed of about 18 km/h (figure 6b).

figure 6 Parachutists photographed (a) before opening the parachute, at about 120 km/h, and (b) after, at about 18 km/h.



a



b

Practice the concepts using the *Flash cards*.

COURSE MATERIAL

1

Answer the following questions.

a What relationship is there between the resultant, the mass and the acceleration?
b What is the definition of the newton (N), the unit of force?
c Why can a motorbike generally accelerate much faster than a family car?
d When can you say that a fall is a free fall?

2

A fully loaded truck will have much more inertia than an empty one.
How will the driver of a fully loaded truck notice this:

a when accelerating?
b when cornering?
c when braking?

IN PRACTICE

3

Many trams have loops hanging in them. Passengers can hold on to these loops. As long as the tram is stationary, the loop hangs down vertically. That is not always the case in a tram that is moving. You can see that the loop is at an angle to the vertical (figure 7).
For the situation in this figure, state what type of motion the tram is undergoing.

○ A The tram is moving forwards at a constant speed.
○ B The tram is moving backwards at a constant speed.
○ C The tram is braking.
○ D The tram is accelerating.

After: IJSO

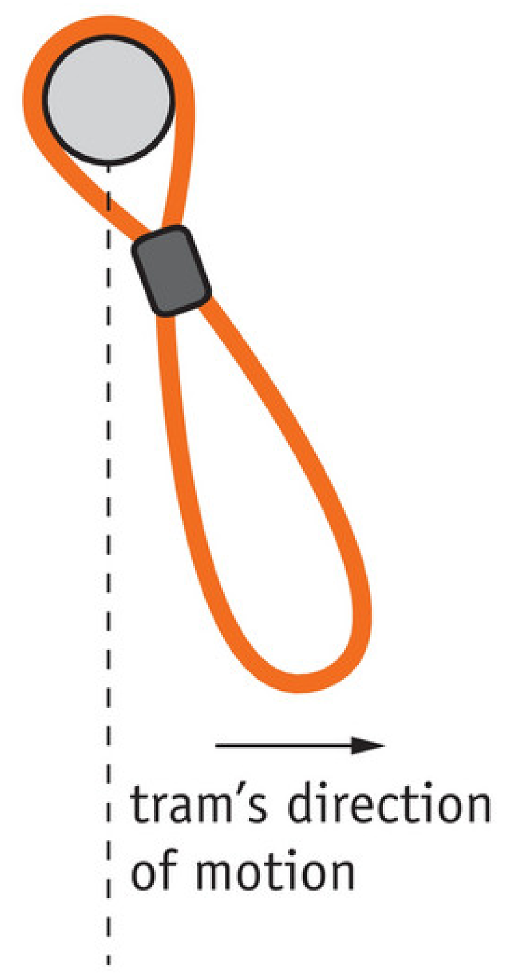


figure 7 A loop in a tram.

4

An electric moped accelerates from 0 to 36 km/h in 2.5 seconds. Including the driver, the mass of the moped is 160 kg. You may assume that the acceleration is uniform.

a Calculate the acceleration.
b Calculate the size of the resultant that is accelerating the moped.

5

The Airbus A380-800 is the world's largest passenger aeroplane. In the run-up to take-off, the motors provide a thrust of $1.2 \cdot 10^6$ N. The mass (including fuel and load) is $5.6 \cdot 10^5$ kg.

a Calculate the acceleration during the first seconds as it takes off. You may ignore any friction forces.
b Show that the speed of the Airbus after 3 s is 6.3 m/s (23 km/h).
c Draw the (*v*,*t*) diagram of the motion of the Airbus during the first three seconds in figure 8.
d Determine the distance covered by the Airbus during the first three seconds.

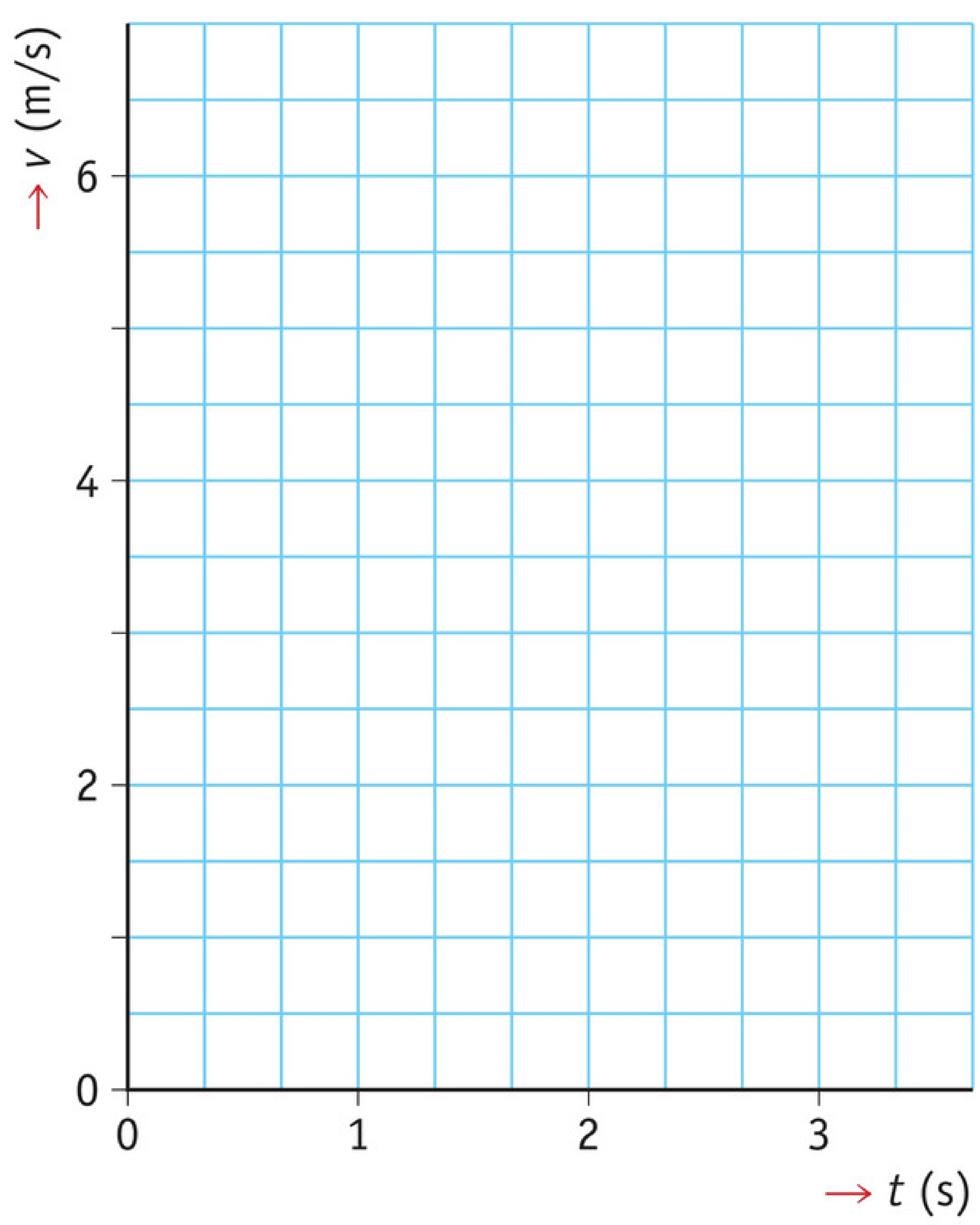


figure 8 The (*v*,*t*) diagram for an Airbus taking off.

6 Read the text in figure 9.

The physics of the world's fastest man

The former 100-metre and 200-metre sprint champion Usain Bolt won eight Olympic gold medals and has won the various sprint events eleven times at the world championships.
The key to Bolt's success was the horizontal force he was able to develop. He came out of the starting blocks with an acceleration of nearly 10 m/s^2, requiring a (horizontal) force of some 817 N.
And Bolt was then one of the few people who could maintain that force over the entire 100 metres. Because the air resistance increased rapidly, his acceleration soon fell away after the start. Between the fourth and fifth seconds, his acceleration had dropped to 0 m/s^2 and he completed the rest of the race at a constant speed of 12.2 m/s.



After: www.gizmag.com

figure 9 An Internet article about the legendary Usain Bolt.

a The text states that Bolt exerts a force.
What does he exert that force on?

b Use the data in the text to make an estimate of the mass of Usain Bolt. Tip: you can ignore any friction forces at the start.

c Use the data from the text to sketch the (v,t) diagram of Usain Bolt in a 100-metre sprint in figure 10.

d During a 100-metre sprint, Bolt covers a distance of 30 m in the first 4.0 s. From the fourth second onwards, he is no longer accelerating and covers the rest of the race at a constant speed of 12.2 m/s.
Calculate Bolt's time in this race.

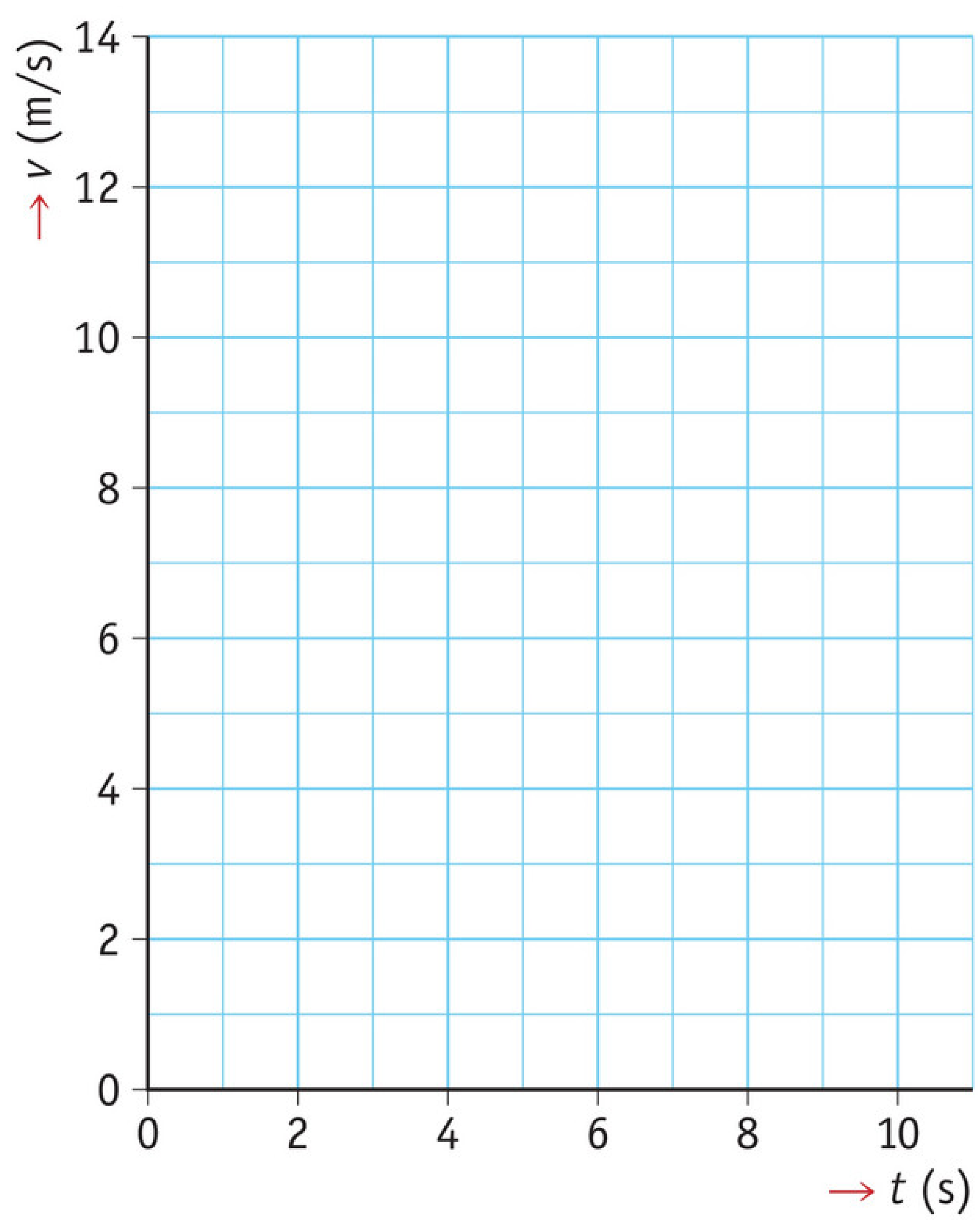


figure 10 Usain Bolt's race.

★ 7

Figure 11 shows you a test report for the Kia ProCeed.

dimensions and weights	
tank volume	50 L
weight	1305 kg
trailer	600 kg
trailer (braked)	1410 kg
performance	
gears	7
acceleration from 0 to 100 km/h	9.4 s
top speed	205 km/h



Source: www.autozine.nl

figure 11 A test report for the Kia ProCeed.

a The term 'weight' is incorrect in physical terms.
What physical variable is it actually describing?

b The test report says how quickly the Kia ProCeed can accelerate from 0 to 100 km/h.
Calculate the size of the (average) resultant acting on the Kia ProCeed.

c The driving force on the car is actually (a lot) greater than the force that you calculated for Exercise b.
Give an explanation for this.

d Figure 11 also states the maximum permissible mass for braked and unbraked trailers.
Explain what is meant by a 'braked trailer'.

e Explain why the mass of a braked trailer is allowed to be much greater than the mass of an unbraked trailer.

f Two Kia ProCeeds A and B accelerate as quickly as possible from stationary. ProCeed A is towing a trailer of 1300 kg, whereas ProCeed B is not towing anything. There are no other differences between the cars.
Show that the acceleration of ProCeed B is roughly 2× greater than the acceleration of ProCeed A.

★ 8

During one of the moon landings in July 1971, the American astronaut David Scott did a simple experiment (figure 12). He dropped a hammer and a feather at the same time from the same height. On a video that was made of this experiment, you can see that the two objects hit the ground on the moon at the same time.

a Explain why the result of the experiment on the moon is different than on Earth.

b Measurements of the video show that the feather and the hammer both land after 1.4 s at a speed of 2.3 m/s.
Calculate the acceleration due to gravity on the moon.

c Show that the two objects were released 1.6 m above the moon's surface.

Test what you know with *Test yourself*.



figure 12 An experiment with falling objects on the moon.

PLUS FALLING IN AIR

9 Susie's hobby is parachuting. During a jump, two forces act on Susie and her parachute: the air resistance ($F_{r,a}$) and the gravity(F_g).

a Susie jumps out of the aircraft. Her speed increases from 0 to 200 km/h.
$F_{r,a}$ is *greater than / the same as / smaller than* F_g.

b Susie falls at a steady speed of 120 km/h for a while.
$F_{r,a}$ is *greater than / the same as / smaller than* F_g.

c Susie's parachute opens. Her speed now decreases from 120 to 18 km/h.
$F_{r,a}$ is *greater than / the same as / smaller than* F_g.

d Susie floats down to the landing area at a steady 18 km/h.
$F_{r,a}$ is *greater than / the same as / smaller than* F_g.

10 Figure 13 shows you how the speed of a skydiver changes during their jump.

a Determine the maximum steady speed of the skydiver during the fall, without the parachute and with the parachute. Explain your answer.

b You can calculate the air resistance using the formula $F_{r,a} = ½ \cdot C_D \cdot A \cdot \rho \cdot v^2$. For more information, see the extra material in Section 3 of Chapter 2.
The mass of the skydiver with the parachute is 100 kg. The frontal cross-section of the skydiver during the fall without the parachute is 0.80 m^2. The density of the air is 1.29 kg/m^3.
Calculate the value of C_D for the skydiver without the parachute.

c The answer that you found in Exercise (b) is different in reality. This is because the density of the air at higher altitudes is less than 1.29 kg/m^3.
Explain whether the answer that you found in Exercise (b) is slightly greater or slightly smaller than the actual value. You can neglect the influence of higher altitudes on gravity.

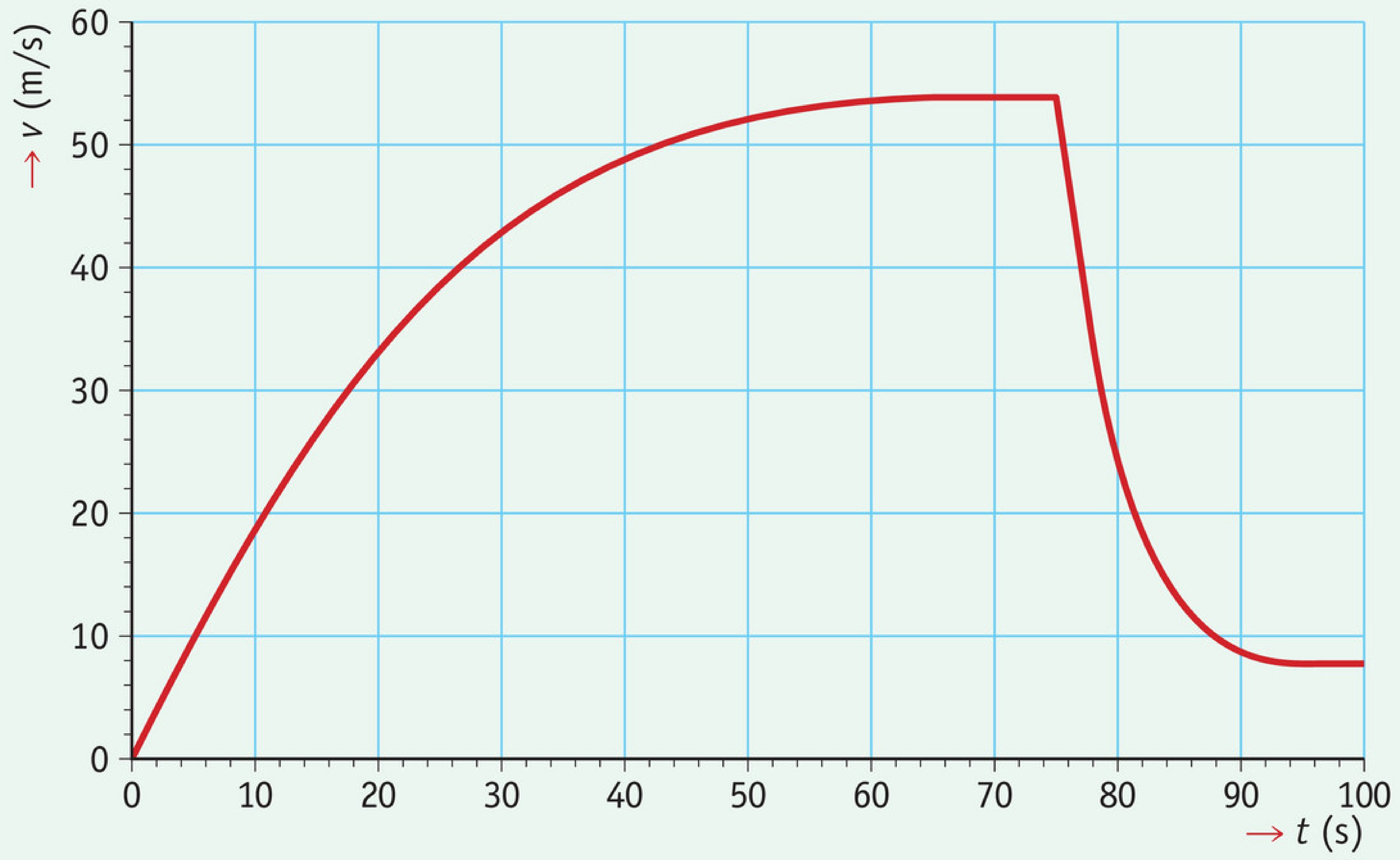


figure 13 The (v,t) diagram of the skydiver.

3 Forces and work

LEARNING OBJECTIVES

4.3.1 You can describe various ways to produce a motive force.
4.3.2 You can explain how the work depends on the distance travelled and the motive force.
4.3.3 You can do calculations with the work, the motive force and the distance.
4.3.4 You can draw and explain the energy flow diagrams for combustion engines and electric motors.
4.3.5 You can explain that the work is equal to the amount of usefully used energy.
4.3.6 You can calculate the efficiency of combustion engines and electric motors.
PLUS 4.3.7 You can do calculations with speed, force and power.

When you are cycling, your muscles provide a driving force or 'motive force'. Your muscles cannot just do that: they need chemical energy. During a long cycling trip, you have to eat regularly to maintain the supply of chemical energy for your muscles.

ENERGY TO MOVE

A motion on Earth does not continue forever like it does in space. There are always resistance forces that act against the motion. That is why on Earth you always need a motive force to stay in motion.

There are various ways of producing such a driving force.

- A car engine uses the chemical energy in petrol to power the car. When the petrol has run out, the motor can no longer produce a motive force. By refuelling, you give the car new chemical energy.
- A train gets electrical energy via the overhead lines (figure 1). The train needs that energy to move. If the voltage on the overhead lines fails, the train comes to a standstill.
- A sailing boat uses the kinetic energy of wind. Because moving air is passing the sails, they provide a driving force. The more wind there is, the more powerfully the boat is driven forwards.

Every means of transport on Earth uses a certain type of energy to get moving and stay moving. When the source of that energy runs out, the motive force stops. The means of transport then comes to a halt fairly quickly.



figure 1 A train gets electrical energy via the overhead lines.

WORK

The motor of a vehicle can only use a proportion of the chemical energy usefully. This part of the energy is used for doing **work**: a force is produced that drives the vehicle forward from the point of departure to the destination. The more work a motor has to do, the more energy it needs.

How much work is done depends on things such as the distance covered. Take an electric locomotive that is pulling thirty wagons, for example. To cover a distance of 500 km, the locomotive needs twice as much energy as to cover a distance of 250 km. If the distance doubles, the work doubles as well.

Besides the distance, the tractive force is also important. If the train had sixty wagons instead of thirty, the tractive force needed would be twice as large. You could achieve that tractive force by putting two locomotives in front of the train. These two locomotives use twice as much energy during the journey as one locomotive with thirty wagons. In this case too, the work is doubled.

You can calculate the work by multiplying the distance by the force exerted. Expressed as a formula:

$$W = F \cdot s$$

where:
- W is the work that the force has carried out, in newton-metres (Nm);
- F is the force acting on the moving object in newtons (N);
- s is the distance that the object has covered in metres (m).

EXAMPLE EXERCISE 1

Anne and Wendy are going on holiday. They attach their caravan to the car and drive to the campsite, 50 km away (figure 2). The car exerts a pulling force of 1.2 kN on the caravan.
Calculate the work done on the caravan.

given $F = 1.2\text{ kN} = 1.2 \cdot 10^3\text{ N}$
$s = 50\text{ km} = 50 \cdot 10^3\text{ m}$

required $W = ?$

working $W = F \cdot s = 1.2 \cdot 10^3 \times 50 \cdot 10^3 = 6.0 \cdot 10^7\text{ Nm}$ (60 MJ)



figure 2 The caravan behind Anne and Wendy's car.

NEWTON-METRES AND JOULES

In figure 3, you can see the energy flow diagram for a car engine. The engine uses just over a third of the chemical energy supplied to do work. The remainder of the energy is lost as waste heat. The engine must be cooled to get rid of that waste heat. Additionally, the hot exhaust gases also take away some of the heat.

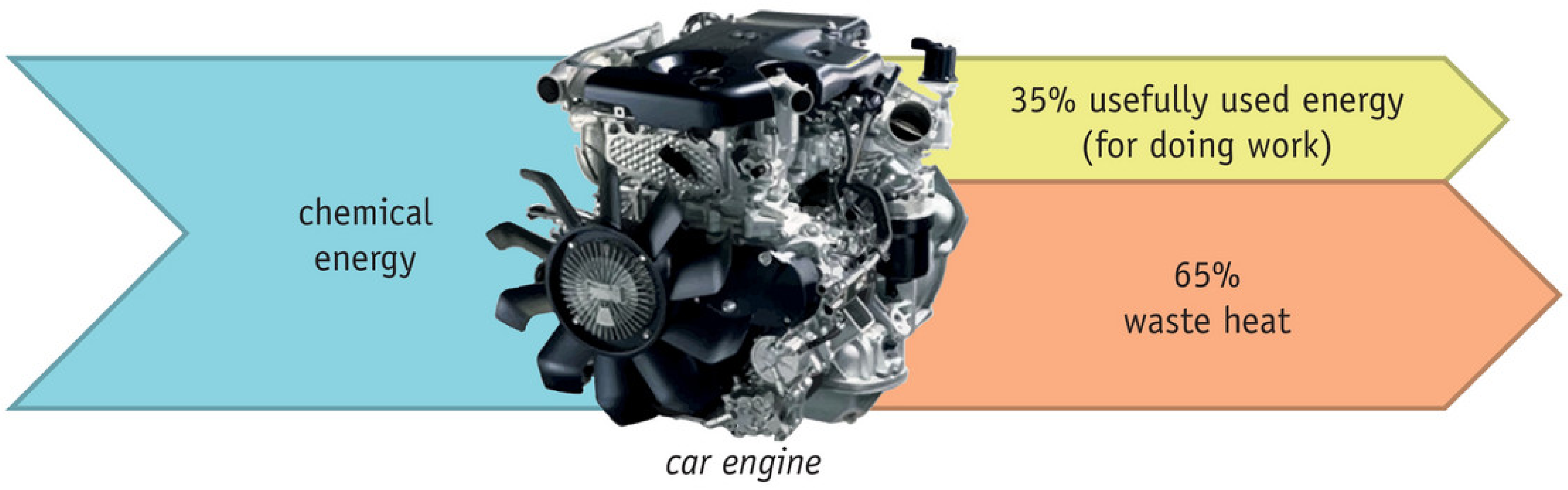


figure 3 The energy flow diagram for a car engine.

The work carried out is proportional to the usefully used energy: for a certain amount of usefully used energy, you always get the same amount of work. That is why the units of work and energy are geared to one another. The unit of energy, the joule, is defined so that it corresponds exactly to the unit of work, the newton-metre: 1 J = 1 Nm

While driving, the usefully used energy is converted into other forms of energy, such as kinetic energy (when accelerating), heat (through resistance forces of the air and the road surface) and sound. Work itself is therefore not a form of energy. Work is a process where energy is converted (with the amount of work done equalling the amount of usefully used energy).

THE EFFICIENCY OF AN ENGINE

In many situations, the work done is easy to determine. You measure the force and the distance and then you use the formula $W = F \cdot s$. This easily lets you find out how much energy is used usefully. After that you can determine the efficiency of an engine, for example. Use the following formula:

$$\eta = \frac{E_{used}}{E_{tot}} \cdot 100\%$$

E_{used} (the usefully used energy) is equal to the work carried out. No conversion is needed because 1 Nm of work corresponds to 1 J of usefully used energy.

In a petrol engine, you can determine the total amount of energy used by measuring the petrol consumed. After that you determine the amount of energy released by multiplying the petrol consumed by the calorific value (which in this type of situation is also called the heat of combustion). In Example Exercise 2, you can see how the efficiency of an electric engine is determined.

EXAMPLE EXERCISE 2

Dimah uses the setup in figure 4 to determine the efficiency of a small electric motor. The motor takes 6.0 s to pull the wood block 1.8 m. During those 6.0 s, the voltmeter reads 1.5 V and the ammeter 0.64 A. The tractive force acting on the wood block is 2.5 N.
Calculate the efficiency of the engine.

1 Calculate E_{tot} = the amount of electrical energy the battery has provided.
given $U = 1.5$ V
$I = 0.64$ A
$t = 6.0$ s

required $E_{tot} = E_{el} = ?$

working $P_{el} = U \cdot I = 1.5 \times 0.64 = 0.96$ W
$E_{el} = P \cdot t = 0.96 \times 6.0 = 5.8$ J

2 Calculate E_{used} = the amount of energy that the motor used usefully.
given $F = 2.5$ N
$s = 1.8$ m

required $E_{used} = W = ?$

working $W = F \cdot s = 2.5 \times 1.8 = 4.5$ Nm

3 Calculate the efficiency of the electric motor.
given $E_{tot} = 5.8$ J
$E_{used} = 4.5$ J

required $\eta = ?$

working $\eta = \frac{E_{used}}{E_{tot}} \cdot 100\ \% = \frac{4.5}{5.8} \cdot 100\ \% = 78\%$

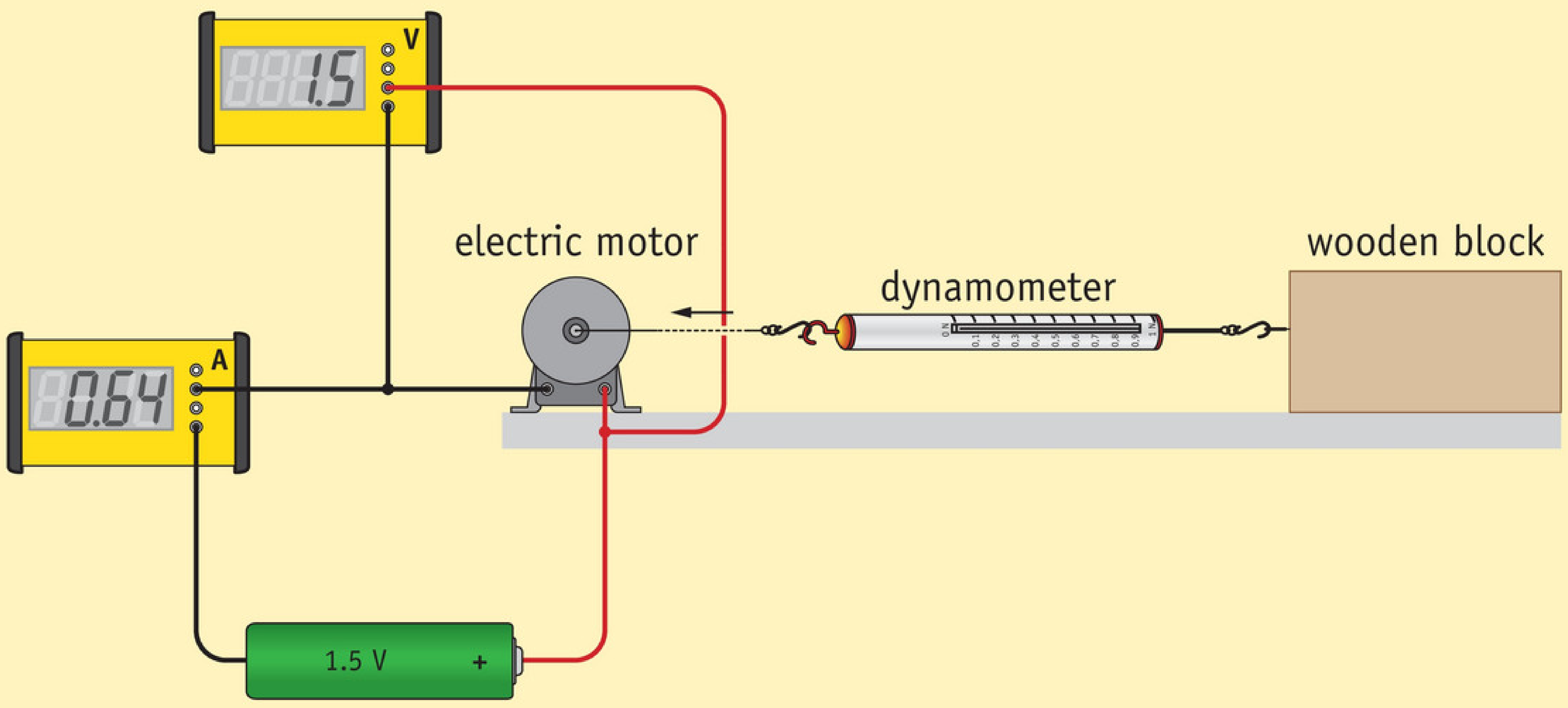


figure 4 Dimah's experiment.

PLUS POWER IN HP

The unit of power, the watt, is named after the Scottish engineer James Watt. At the end of the eighteenth century, he made an important contribution to the development of steam engines. They often had to take over work previously done by horses (figure 5), which is why the assessment of a steam engine looked at how many horses it could replace.



figure 5 Before the steam tram and electric tram, trams were pulled by horses.

James Watt introduced the unit **horsepower** for this, or hp in short. And as the name suggests, this is also a unit of power. 1 hp is the work that a workhorse could provide per second – its useful power, in other words. Expressed as a formula:

$$P_{used} = \frac{W}{t}$$

where:
- P_{used} is the useful power that the machine provides in watts (W);
- W is the work that the horse (or later, the machine) carries out in newton-metres (Nm);
- t is the time in seconds (s).

EXAMPLE EXERCISE 3

James Watt defined 1.0 hp as the power of a horse capable of hoisting a mass of 150 kg 30 m high in 1.0 minute.
Calculate how many watts 1.0 hp is.

given $m = 150$ kg
$t = 1.0$ min $= 60$ s
$s = 30$ m

required $P_{used} = ?$ W

working The gravitational force acting on a mass of 150 kg is:
$F_g = m \cdot g = 150 \times 9.8 = 1470$ N
The work needed to raise that mass 30 m is:
$W = F \cdot s = 1470 \times 30 = 44{,}100$ J
The power that is needed to do this in one minute is:
$P_{used} = \frac{W}{t} = \frac{44{,}100}{60} = 7.4 \cdot 10^2$ W
in other words, 1.0 hp $= 7.4 \cdot 10^2$ W

Now, almost 250 years after the Industrial Revolution, the horsepower is still used, for example for the power of car engines (figure 6).



figure 6 Lewis Hamilton's Formula 1 Mercedes has a maximum power of $1.0 \cdot 10^3$ hp, so it could replace a thousand horses.

Practice the concepts using the *Flash cards*.

COURSE MATERIAL

1

Answer the following questions.

a Why do you always need a motive force to keep moving on Earth?
b How can you calculate the work done on the moving object?
c What is the relationship between work and energy?
d How can you tell that a car engine does *not* use a large proportion of the chemical energy supplied usefully?

2

You can determine the power of an engine by taking measurements and making calculations, just like with other energy converters.

a How can you determine how much energy an engine uses usefully?
b How can you determine how much chemical energy a petrol engine uses?
c What formula can you use to calculate the efficiency?

IN PRACTICE

3

Transporting people and goods needs large amounts of energy.

a Write down three means of transportation that use chemical energy.
b Write down three means of transportation that use electrical energy.
c In the past, sailing ships were widely used for transport. What type of energy does a sailing ship use?

4

Figure 7 shows you a situation in which a lot of work is done.

a What provides the motive force in this situation?
b What type of energy is needed to produce that force?
c In what form is this energy supplied to the body?
d How can the mountain biker tell that a lot of waste heat is being produced?
e How does the body make sure that it does not get overheated by that waste heat?



figure 7 A mountain biker during a race.

5 Figure 8 shows a boat being pulled along during a trip for old cargo ships. To pull the ship along the canal at a steady speed of 2.5 m/s, the men must exert a traction force of 700 N in total. The canal they are pulling the boat along is 5.5 km long.

a What force in particular is working against this motion?
b How large are all resisting forces together?
c How much work do the men do?



figure 8 Two men in pulling a barge.

6 Calculate the work done in the following situations.

a A toy locomotive pulls five wagons around a model railway track once. The tractive force is 0.10 N and the distance is 4.6 m.
b Peter pulls a cart with two of his friends in it along the street. The traction force is 52 N and the distance is 85 m.
c Two horses pull a covered wagon full of tourists along a dirt road. The traction force (from both animals together) is 1.3 kN and the distance is 1.2 km.
d A diesel locomotive pulls a freight train from Amsterdam to Arnhem. The traction force is 150 kN, the distance is 98 km.
e An ocean tug tows an oil rig from Rotterdam to the Persian Gulf. According to a press release, the tractive force is 1250 kN and the distance is 13,000 km. Assume that these numbers are both reliable to three significant figures.

7 An electric motor is hoisting a block. It exerts a constant lifting force of 2.0 N. The motor runs on a voltage of 9.0 V and the current through the motor is 0.20 A.

a Calculate the power drawn.
b The motor takes 5.0 seconds to raise the block by 180 cm.
Calculate how much electrical energy the motor uses in those 5.0 seconds.
c Calculate the work done by the motor.
d Calculate the efficiency of the motor.

8 The performance of a diesel engine is being measured in a test at a car factory. During the test, the work done by the engine is $5.7 \cdot 10^7$ Nm. Under these conditions, the engine's efficiency is 45%. The calorific value of diesel fuel is 36 MJ/litre.

a Calculate how much chemical energy the engine used during the test.
b Calculate how many litres of diesel fuel the engine used during the test.

★ 9 At a speed of 90 km/h, a car uses 1.0 litre of petrol for a distance of 12 km. At this speed, the driving force is 950 N. The calorific value of petrol is 33 MJ/L.
Calculate the efficiency of the car at a speed of 90 km/h.

Test what you know with *Test yourself*.

PLUS POWER IN HP

10 Another definition of the horsepower is the power needed to hoist a mass of 75 kg slowly, where 'slowly' means at a speed of 1.0 m/s.

- **a** Show that it also follows from this that 1.0 hp is $7.4 \cdot 10^2$ W.
- **b** Show that you can calculate the useful power of, for example, a car engine using the formula $P_{used} = F \cdot v$, where F is the motive force that the engine exerts and v is the steady speed at which the car is being driven.

11 According to figure 6, Lewis Hamilton's Formula 1 Mercedes has a maximum power of $1.0 \cdot 10^3$ hp.

- **a** Calculate the maximum power of Lewis Hamilton's car in kW.
- **b** Mercedes claim that the engine of Hamilton's Formula 1 car has an efficiency of 50%. Normal petrol is used during the races. If you use 1.0 litre of petrol, it provides $3.3 \cdot 10^7$ J.
  Calculate how many litres of petrol are needed if the car is driven at maximum power for 15 minutes.
- **c** Calculate the driving force that the engine exerts if Lewis Hamilton drives at a speed of 350 km/h on the straight part of the circuit.

4 Braking and collisions

LEARNING OBJECTIVES

4.4.1 You can explain the relationship between the reaction distance, braking distance and stopping distance.
4.4.2 You can determine the stopping distance by looking at the (v,t) diagram of a braking vehicle.
4.4.3 You can calculate the average braking force on the people in the car.
4.4.4 You can explain two ways of keeping the decelerations during a collision as small as possible.
4.4.5 You can list three safety features a car has and explain what they do.
4.4.6 You can do calculations with pressure, force and the area of the contact surface.
PLUS 4.4.7 You can calculate the work needed for a given change in speed.

The governmental authorities have taken all sorts of measures to make road traffic safer. For example, cars may not go faster than 30 km/h in some built-up areas. There's a good reason for that: the consequences of a collision at a speed of 50 km/h are similar to a fall from a ten-metre building.

DETERMINING THE STOPPING DISTANCE

When a car driver wants to stop, it takes a little time before the brake pedal is pressed and the brakes are applied. The time required for this is called the **reaction time**. During the reaction time, the car keeps going at a constant speed. The distance that the car covers during this uniform motion is called the **reaction distance**.

After the brake pedal has been pressed, the car decelerates virtually uniformly until it is stationary. The distance that the car covers during this uniform deceleration is called the **braking distance**. The total stopping distance therefore consists of two parts: the reaction distance and the braking distance:

stopping distance = reaction distance + braking distance

The faster someone is driving, the greater the reaction distance and the braking distance will be, and therefore the greater the stopping distance (figure 1).

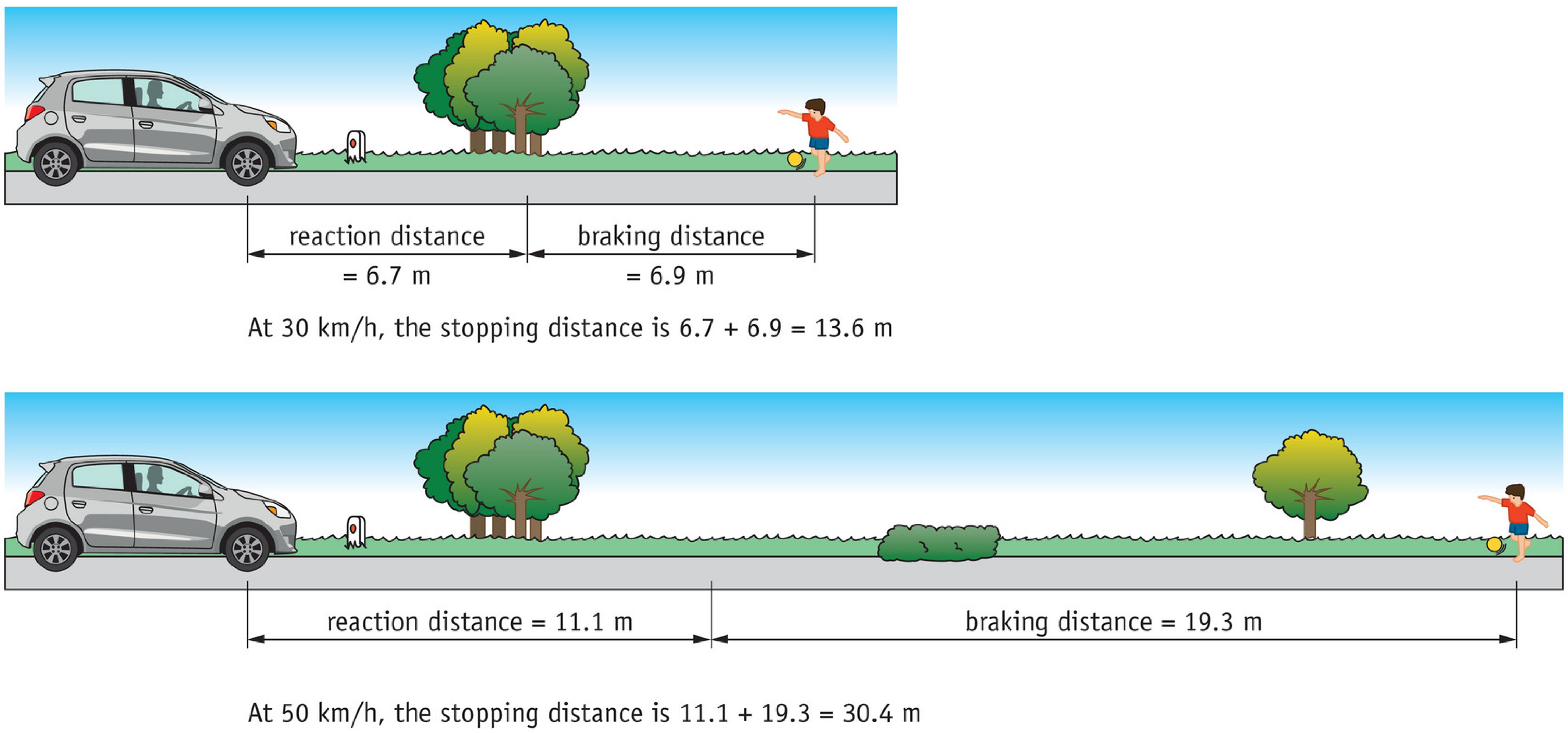


figure 1 The stopping distance at a reaction time of 0.8 s and a deceleration of 5 m/s^2.

Figure 2 shows you the (v,t) diagram of a car that is braking for a zebra crossing. As you can read off from the diagram, the reaction time is 0.8 s. After that, the care decelerates for 3.0 s until it is stationary. You can determine the stopping distance by reading the area under the curve for the (v,t) diagram. If you do that for figure 2 (after you have converted the speeds from km/h to m/s), you get a stopping distance of 34.5 m. Prove for yourself that this is correct.

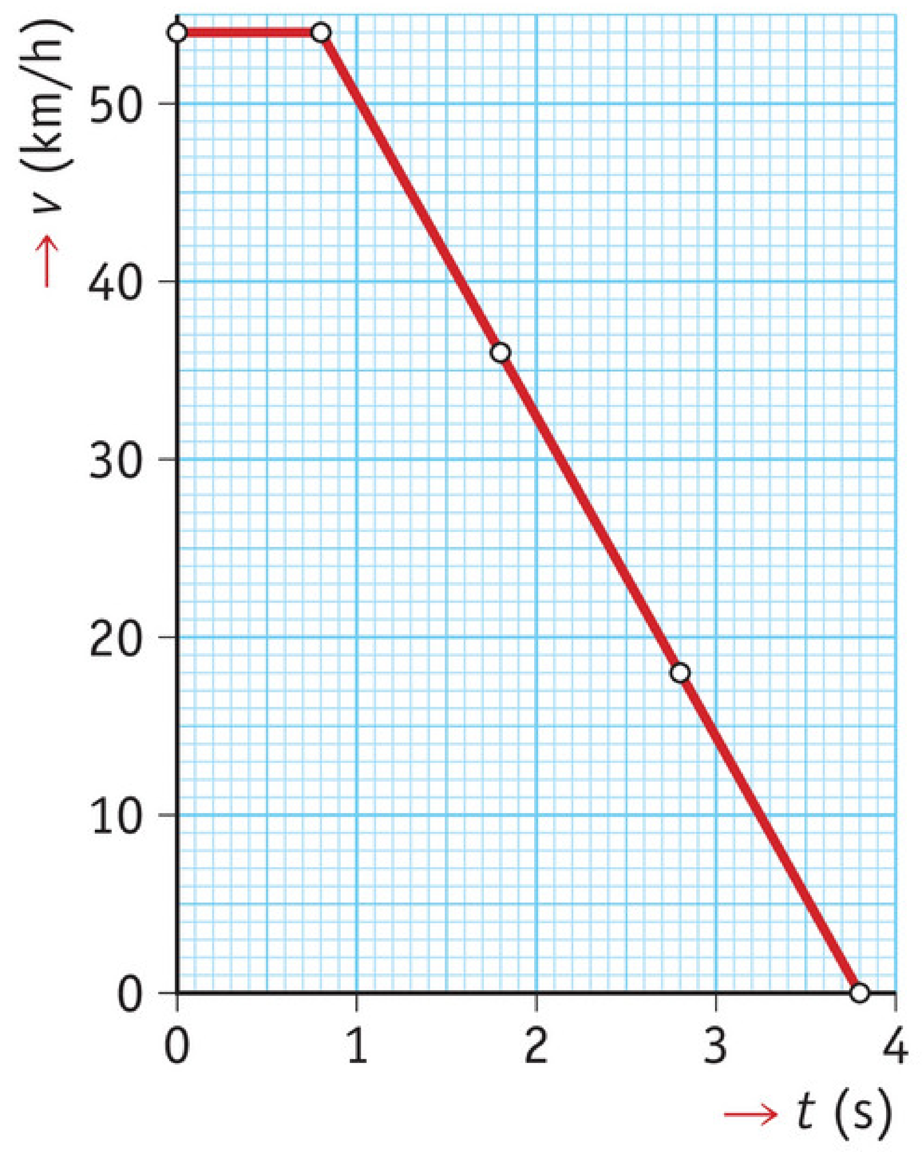


figure 2 Stopping for a zebra crossing: first the reaction, then the braking.

COLLIDING

During a collision, the people in a car are brought suddenly to a halt. The (average) deceleration a is very high. That means that a large braking force F acts on the people in the car during the collision, even if the speed does not feel that fast. Large forces like these can cause serious injuries.

EXAMPLE EXERCISE 1

In a crash test with a car, a crash dummy (80 kg) comes to a standstill in 60 ms (figure 3). The car's speed is 32 km/h. The dummy is held in place by a belt that does not stretch.
Calculate the average braking force on the dummy.

given $m = 80$ kg
$v_i = 32$ km/h $= 8.9$ m/s
$v_f = 0$ m/s
$\Delta t = 60$ ms $= 0.060$ s

required $F = ?$

working $\Delta v = v_f - v_i = 0 - 8.9 = -8.9$ m/s

$$a = \frac{\Delta v}{\Delta t} = \frac{-8.9}{0.060} = -148 \text{ m/s}^2$$

$$F_{braking} = m \cdot a = 80 \times -148 = -12 \cdot 10^3 \text{ N} = -12 \text{ kN}$$

The force in this example is greater than the force of gravity on a mass of 1200 kg. We have assumed here that the seatbelt does not stretch. In reality, a seatbelt does stretch in a collision. The deceleration therefore takes longer and the average force acting on the people in the car is significantly less.



figure 3 Test dummies in a car after a crash test.

DRIVING SAFELY

In a collision, it is important to keep the deceleration as small as possible. This lets you limit the braking forces on the body and thereby the risk of injury. By definition, a is equal to $\Delta v : \Delta t$. That means that you can make a smaller in two ways.

- by making Δv as small as possible;
- by making Δt as large as possible.

Making Δv smaller is the responsibility of the driver. They have to assess the dangers and adjust their driving speed to suit. If there is an increased risk of collisions, you should slow down. That makes it easier for you to avoid other road users. If a collision does occur, the deceleration and therefore the braking force is also less.

Extending Δt is a task for car designers. They have thought up all kinds of ways to make the actual collision time as long as possible. The front and rear of a car are for example designed so that they can collapse inwards easily when there is a collision (figure 4). These **crumple zones** make the collision time longer and the braking forces are correspondingly less.

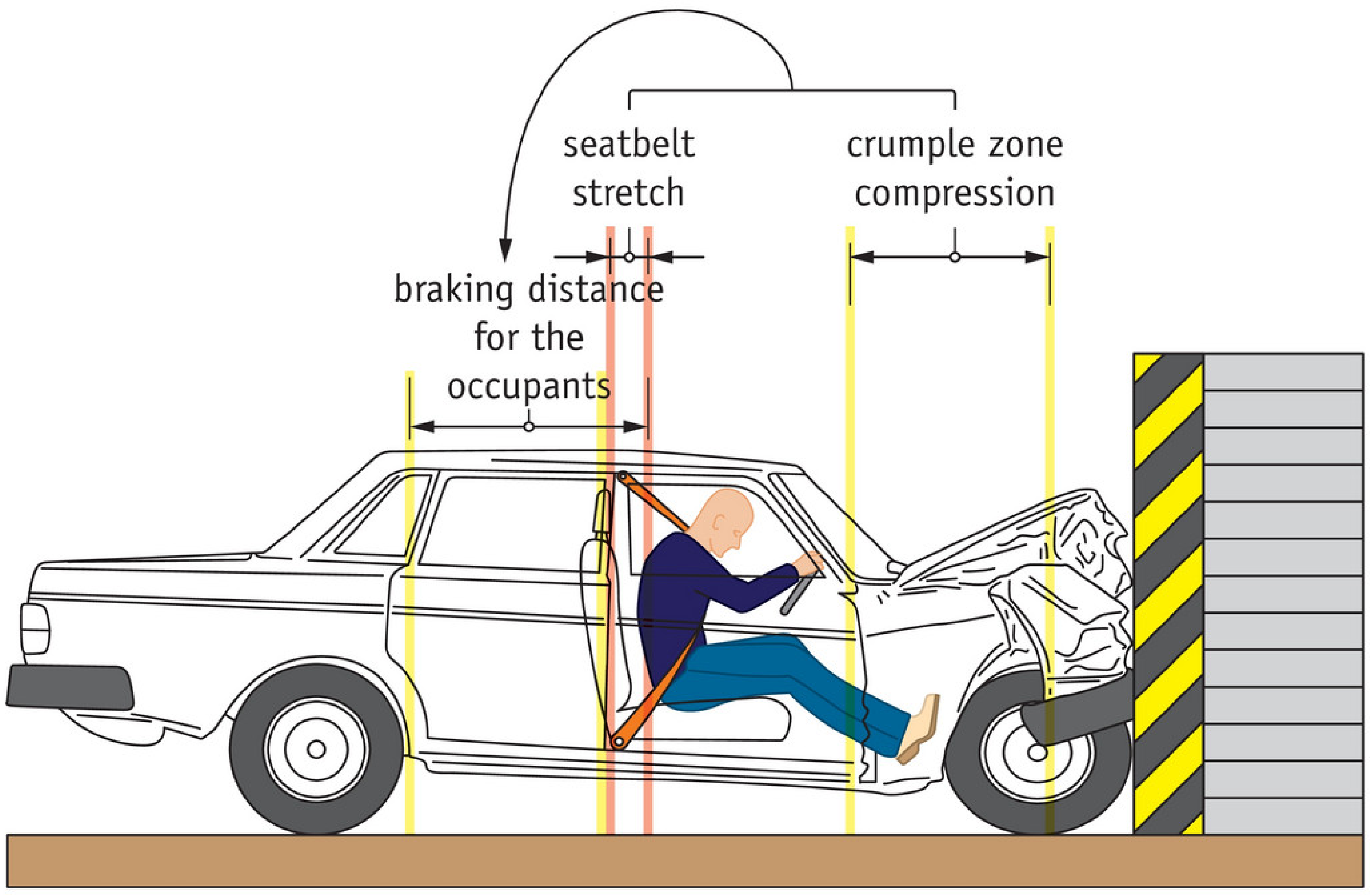


figure 4 A crash test. You can see how the deceleration distance (and therefore the deceleration time) is made as long as possible for the occupants.

PRESSURE

Safety belts and airbags also make sure that the occupants are decelerated along with the car itself, which has a relatively long collision time, rather than all at once when they hit the windscreen, as is the case in an extremely short collision time. On top of that, the seatbelts and airbags spread the braking forces out over a larger area. That means that the pressures exerted are lower, reducing the risk of injury.

If a force F acts on an area A, you can calculate the pressure p using:

$$p = \frac{F}{A}$$

where:

- p is the pressure in newtons per square metre (N/m^2) or pascals (Pa);
- F is the total force acting on the area in newtons (N);
- A is the size of the area in square metres (m^2).

Safety belts are made as wide strips. This creates a large contact surface area between the belt and the body. This makes the **pressure** on the body as small as possible. A thin belt would concentrate the braking force in a small area, with more pressure there as a result.

EXAMPLE EXERCISE 2

The contact surface area where the seatbelt presses on the dummy in Example Exercise 1 is 300 cm^2.

Calculate the (average) pressure on the dummy while braking.

given $F_{avg} = 12\ kN = 12 \cdot 10^3\ N$

$A = 300\ cm^2 = 3.00\ dm^2 = 0.0300\ m^2$

required $P = ?$

working $p = \frac{F_{avg}}{A} = \frac{12 \cdot 10^3}{0.0300} = 4.0 \cdot 10^5\ Pa$

PLUS THE WORK DONE WHEN BRAKING

Objects that move have **kinetic energy.** You can calculate the kinetic energy of a car (or any other moving object) using the formula:

$$E_k = ½\, m \cdot v^2$$

where:

- E_k is the kinetic energy of the object in joules (J);
- m is the mass of the object in kilograms (kg);
- v is the speed of the object in metres per second (m/s).

The term kinetic energy comes from the Greek verb *kinein* = to set in motion. The abbreviation E_k is derived from that.

When decelerating, the braking force means that the kinetic energy is continuously decreasing. The work of the braking force is equal to the decrease in kinetic energy here: $W = \Delta E_k$

You can also write this as:

$$W = F \cdot s = E_{k,f} - E_{k,i} = ½\, m \cdot v_f^2 - ½\, m \cdot v_i^2$$

In which v_i refers to the initial speed (when braking starts) and v_f is the final speed (when braking stops). When an object slows to a stop, all its kinetic energy is converted into heat. In that case, v_f is equal to 0 m/s and the following applies:

$F \cdot s = 0 - ½\, m \cdot v_i^2$, or in short: $F \cdot s = -½\, m \cdot v_i^2$

You can use this formula to calculate the braking force if the initial speed and the braking distance (the distance covered while braking) are given. You can see from the formula that the calculated braking force is negative. This force always acts against the direction of motion.

Practice the concepts using the *Flash cards*.

COURSE MATERIAL

1

Answer the following questions.

- **a** What do you call a motion where the speed is decreasingly evenly?
- **b** What is meant by the statement that "The deceleration of the car is 5 m/s^2"?
- **c** What two distances do you have to add together to find the overall stopping distance?
- **d** What factors affect the deceleration that the body is subjected to during a collision?
- **e** What is the unit of pressure?

2

A crumple zone and safety belt can be used to increase the safety of the people inside the car.

- **a** Explain what happens to the crumple zone of a car during a collision.
- **b** Why does a crumple zone reduce the risks for the occupants?
- **c** Explain why a seatbelt reduces the force of the collision on the body.

IN PRACTICE

3

Three uniform decelerations are described below.
Work out what the deceleration is in each of the motions.

- **a** Norah is cycling at a speed of 5 m/s. She stops pedalling. After 20 s, her speed has dropped to 2.3 m/s.
- **b** A car that is going at 72 km/h stops for a traffic light. The car is at a standstill after 7.0 s.
- **c** A car travelling at 50 km/h hits a tree. The driver is stationary 0.30 s later.

4

Read the newspaper article in figure 5.

a Explain whether the occupant who was severely injured fell forwards or backwards.

b What safety requirement had the occupant not observed?

c The bus driver (mass 95 kg) braked with a deceleration of 6.0 m/s^2. He was wearing a seatbelt.
Calculate the force that the seatbelt exerted on the driver.

d The contact area between the belt and the driver was 250 cm^2.
Calculate the pressure that the seatbelt exerted on the driver.

figure 5 The consequences of sudden braking.

Bus has to brake; four passengers injured

Almere – Four people in a bus in Almere Harbour were injured on Tuesday when the driver suddenly had to brake for a crossing moped rider. According to the police, one of the passengers who fell was severely injured. A second passenger also had to be taken to the hospital.
The bus was driving along Bivak in Almere Harbour shortly before half past eleven. Although the driver braked sharply, he could not prevent a collision. According to the police, the moped rider was unharmed.
The police are still investigating how exactly the accident occurred and are looking for witnesses.

Source: www.omroepflevoland.nl

5

A car driver sees a hare run out onto the road a short distance ahead. He tries to stop for the animal. Figure 6 shows you the (v,t) diagram of his car, from the moment (t = 0 s) that he spots the hare.

a Read off the reaction time from figure 6. The reaction time is .... s.

b Determine the deceleration as the car brakes.

c The mass of the car plus driver is 1250 kg.
Calculate the braking force that is exerted on the car.

d Determine the stopping distance.

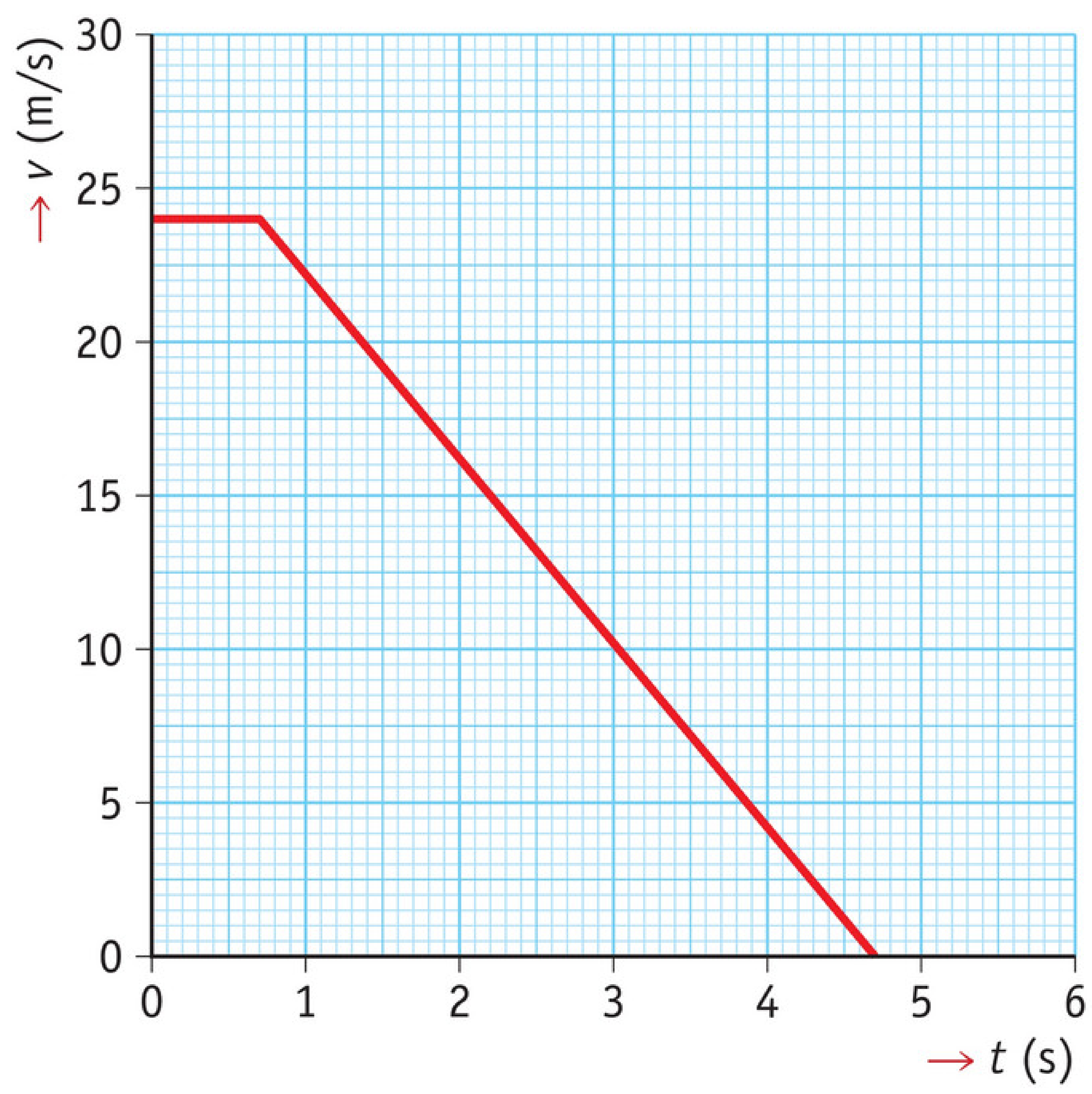


figure 6 A car driver stops for a hare.

6 The airbags in a car are inflated extremely quickly if the car is subjected to a deceleration of more than 50 m/s^2. The airbag stops your body so that the seatbelt does not have to brake your body all by itself (figure 7). The airbag can be compressed inwards, just like if you press on a balloon with your finger.

a The airbag reduces the risk of the people in the car being injured in a collision. Say how physics explains this.

b Say how physics explains this, using the term 'pressure'.

c In a crash test, a car hits a concrete wall at a speed of 20 km/h. The car is brought to a halt in less than 0.10 s. The crumple zone of the car is made so that the car's deceleration is uniform during the collision.
Do a calculation to see whether the airbag will be inflated in this collision or not.

d Show that the crumple zone of the car gets compressed by 28 cm in this crash test.
Tip: first draw the (v,t) diagram of this motion in figure 8.



figure 7 An airbag being tested in a crash test.

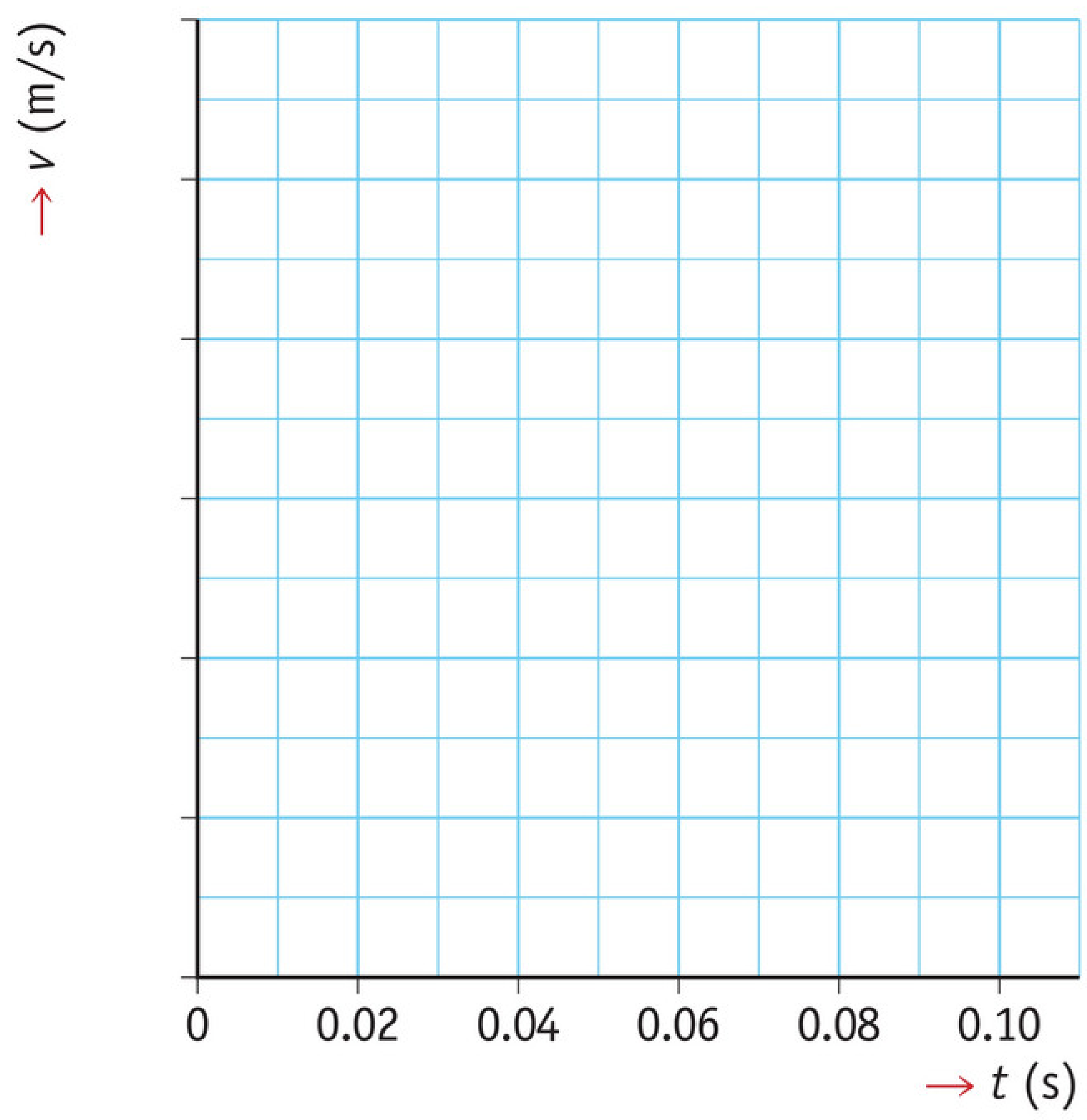


figure 8 The (v,t) diagram for a crash test.

★ 7

Braking tests with twelve e-bikes and twelve different cyclists show that the 'Keola Delft' has the greatest average deceleration when braking.

a Think up a reason why the deceleration is not the same for all cyclists.

b At a speed of 20 km/h, the average deceleration of all cyclists during the test is 13.9 m/s^2.
Use a calculation to show that the average braking time during this test is 0.40 s.

c Calculate the average braking distance during this test.

d You can reach speeds of up to 25 km/h on an e-bike. That is why more and more e-bike users are starting to wear helmets. The helmets have a hard outer shell and an inside made of soft, springy material.
Use your knowledge of physics to give two reasons why wearing a helmet like this reduces the risk of serious injury.

e An e-biker without helmet has a fall while cycling. His head hits the ground. The part of his head that hits the ground has an area of 4.4 cm^2.
By what factor would the pressure on this part of his head be reduced if he had been wearing a helmet? (Size 58 = this is the circumference of the head in cm.) Make a few assumptions yourself for this assignment and use the formula for the surface area of a sphere in your solution: $A = 4 \cdot \pi \cdot r^2$.

★ 8

During a crash test, a car driving at 72 km/h hits a concrete wall. There is a crash test dummy of 75 kg in the car, wearing a seatbelt just as a normal occupant would. Figure 9 shows you how the average force that decelerates the dummy varies depending on the distance that the dummy travels during the collision.

a The dummy covers a distance of 0.60 m during the collision.
Determine the (average) braking force on the dummy.

b The dummy is secured with a seatbelt 6.0 cm wide that is in contact with the dummy over a length of 1.2 m.
Calculate the average pressure of the dummy on the belt during the collision.

c Calculate the (average) braking deceleration.

d The 0.60 m that the dummy travels during the collision is in part due to the crumple zone (50 cm) and in part due to the seatbelt stretching (10 cm).
Determine what the force on the dummy would have been if the seatbelt did not stretch.

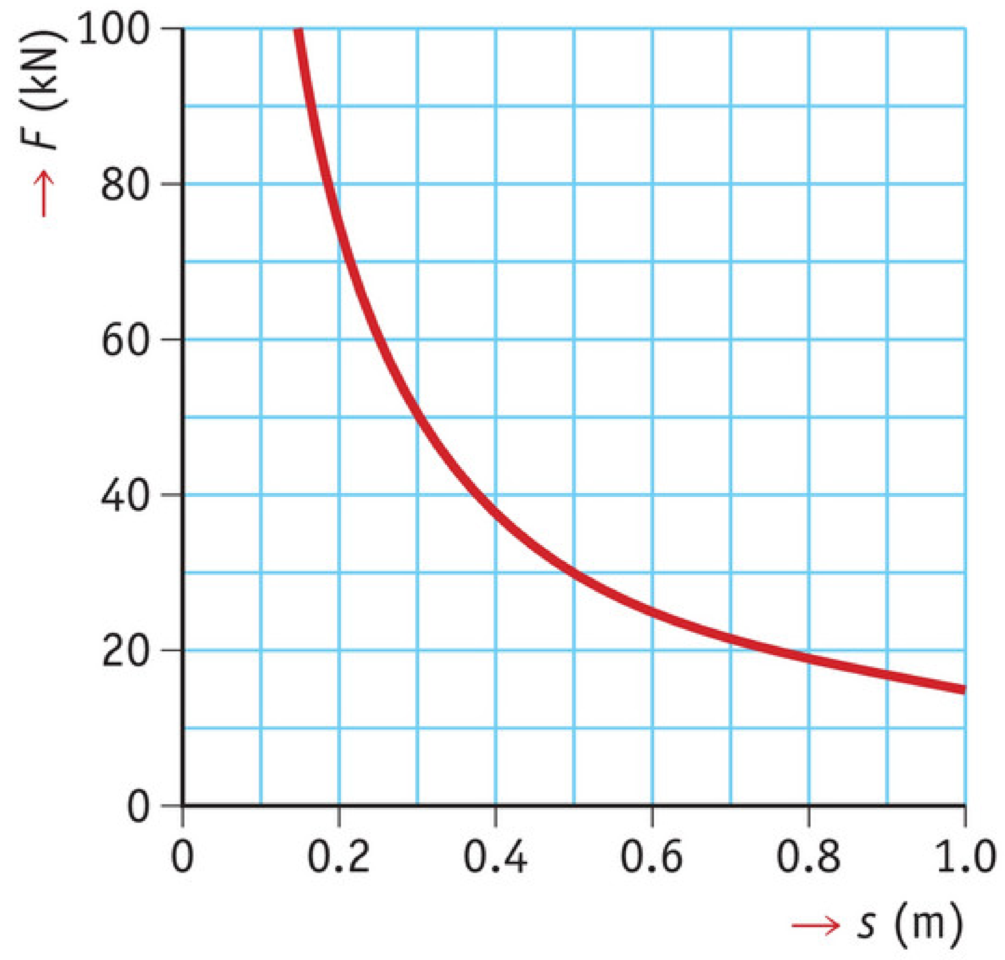


figure 9 The relationship between the braking distance in a collision and the force on the crash test dummy.

Test what you know with *Test yourself*.

PLUS THE WORK DONE WHEN BRAKING

9

a Explain what happens to the braking force if you collide at twice the speed with the same collision distance.

b In a collision, the braking force on the driver is 24 kN. The mass of the occupant is 80 kg, the collision distance is 30 cm.
Calculate the speed of the driver before the collision.

10

In a collision, the people in a car are brought to a halt over a very short distance.

a The form of energy that the kinetic energy of the occupants is converted into is ....

b In a collision, an occupant (mass = 80 kg) comes to a standstill over a distance of 0.40 m. The speed before the collision was 72 km/h.
Calculate the braking force on the occupant.

c In collisions, the deceleration on the occupant is often expressed as a multiple of the acceleration due to gravity *g*.
Calculate the deceleration on the occupant, expressed as a multiple of the acceleration due to gravity *g*.

11

In a crash test, a (*v*,*t*) diagram is made of the colliding car (figure 10). The mass of the car is 900 kg.
Determine the (average) force of the collision on the car using the diagram. Do this using the formula $F \cdot s = -\frac{1}{2}\, m \cdot v_i^2$. Hint: read the extra material of Section 4.1 to find out how you can determine the distance covered using the (*v*,*t*) diagram.

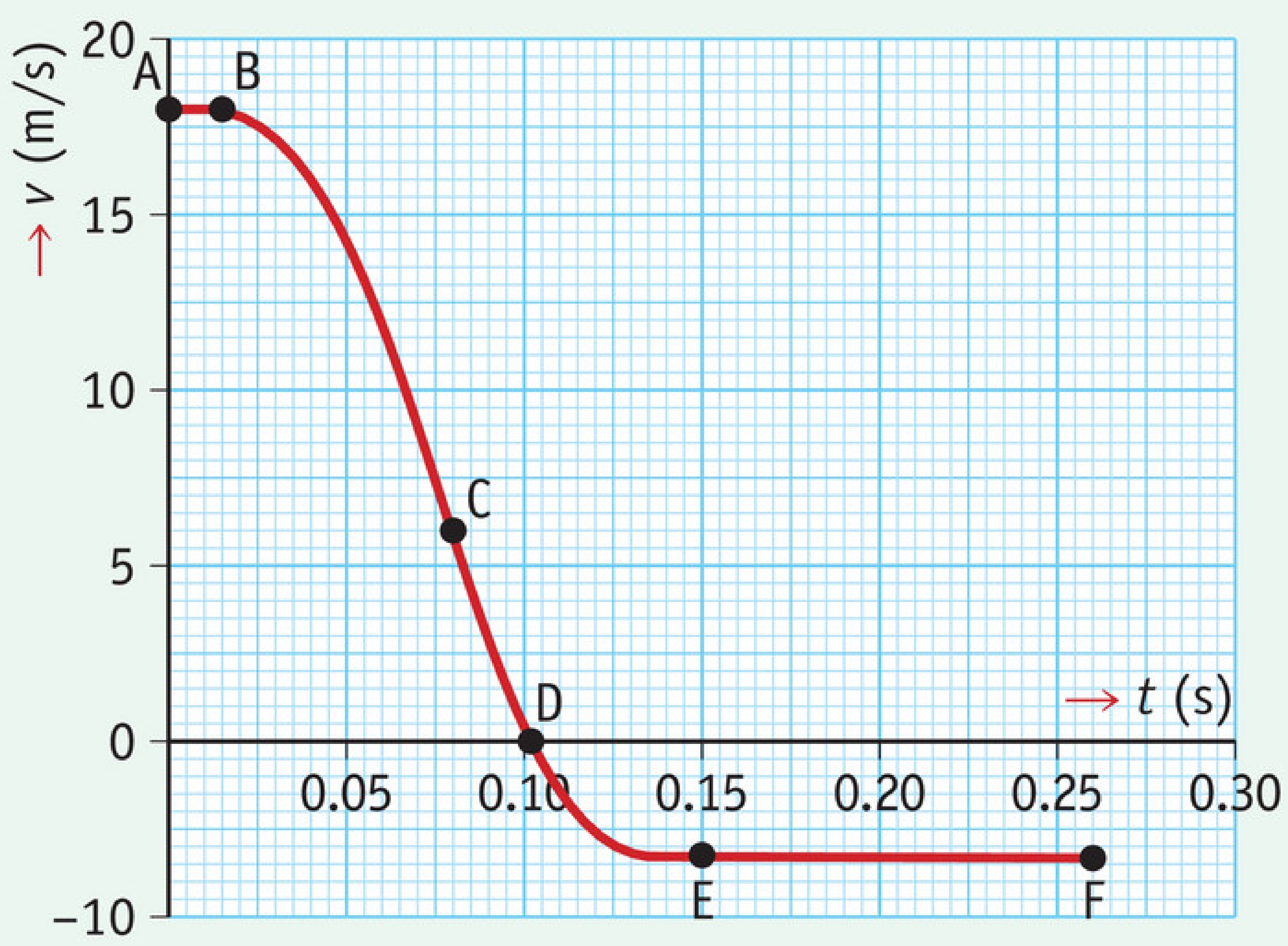


figure 10 The (*v*,*t*) diagram of the crash test.

Experiments

EXPERIMENT 1 DETERMINING THE ACCELERATION

30 minutes

Introduction

A marble rolls along a steel bar with an L-shaped profile. Because the marble rolls easily along the L-profile, there is almost no resistance due to friction. If you put the L-profile at a slight slope, the marble will slide down the track under a steady acceleration.

Purpose

In this experiment, you will be determining the acceleration of the marble down an L-profile.

Requirements

- ☐ marble
- ☐ L-profile (for example for plastering)
- ☐ masking tape
- ☐ stopwatch
- ☐ ruler or measuring tape

Doing the experiment and writing it up

- Build the experiment as shown in figure 1. Mark the starting point and the end point of the motion using masking tape.
- Measure the distance between the starting point and the end point.

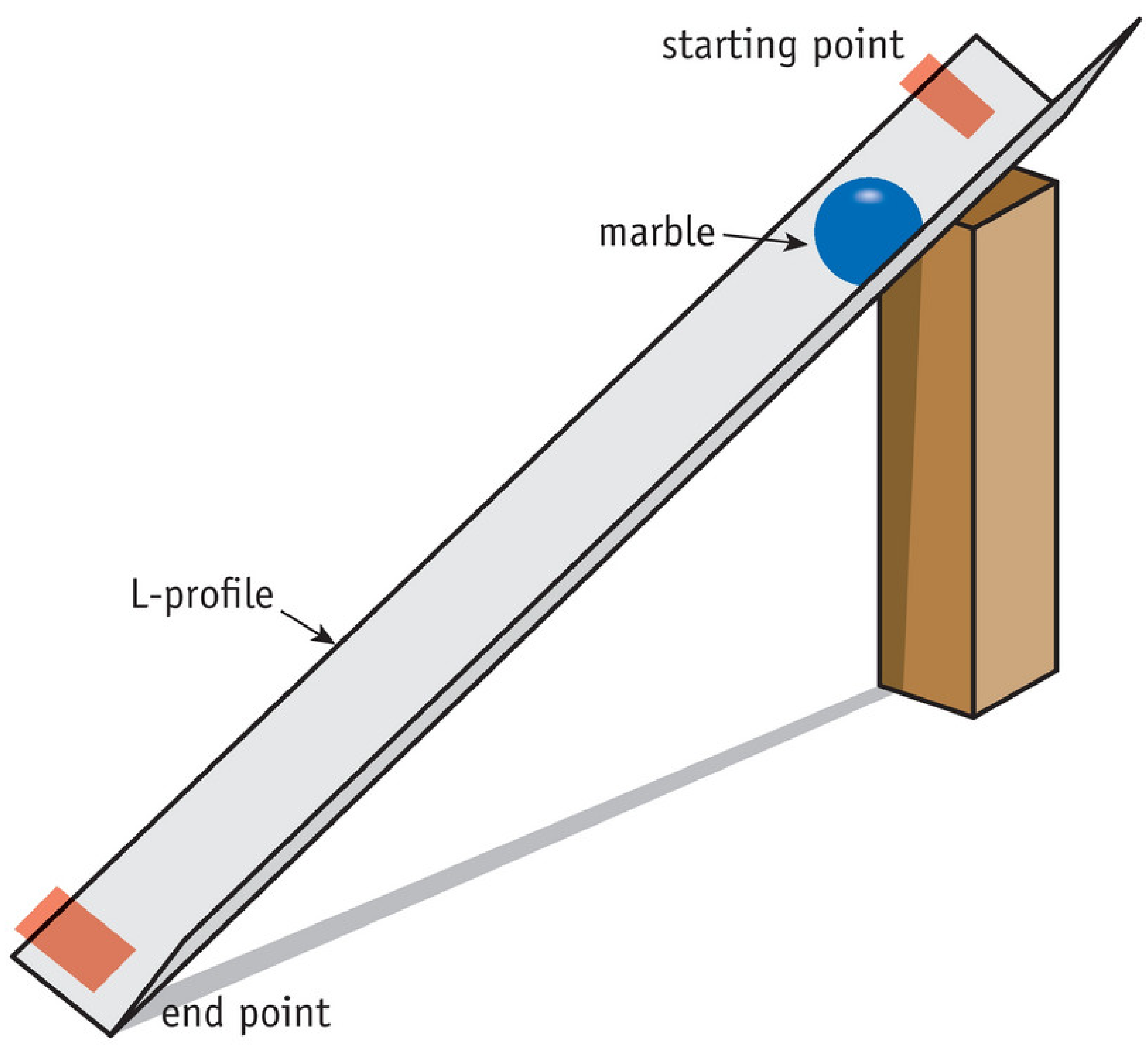


figure 1 The setup for Experiment 1.

1 Write down the measured distance in the correct place in table 1.

table 1 The measurements for Experiment 1.

measurement	distance (m)	time (s)
1		
2		
3		
4		
5		
average		

- Place the marble at the starting point.
- Release the marble and start timing it at that moment.
- Stop the timer when the marble goes past the end marker. Write down the measured time in the correct place in table 1.
- Carry out this measurement five times.

2 Calculate the average time. Write this down in table 1.

3 Calculate the marble's average speed v_{avg}.

....

....

....

4 The final speed of the marble is 2× the average speed.
Calculate the final speed v_f of the marble.

....

....

....

5 Now calculate the acceleration of the marble.

....

....

....

Your teacher will tell you whether or not you have to write up a report on this experiment.

EXPERIMENT 2 ACCELERATION AND FORCE

30 minutes

Introduction

The trolley on an air-cushion track floats just above the rail on a cushion of air. That makes the resistance forces acting against the motion negligibly small: the resultant is the same size as the driving force.

Purpose

You are investigating the relationship between the resultant force on the trolley and its acceleration.

Requirements

- ☐ air-cushion track
- ☐ trolley
- ☐ weight carrier
- ☐ weights
- ☐ pulley
- ☐ cord
- ☐ stopwatch or light gate with an electronic timer

Doing the experiment and writing it up

- Build the experiment as shown in figure 2.

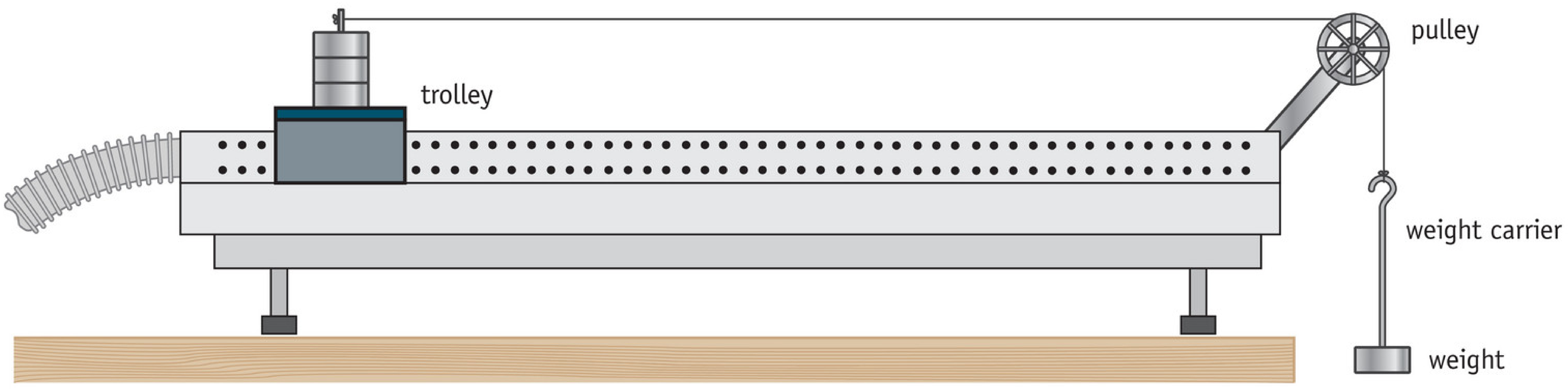


figure 2 The setup for Experiment 2.

Measurement 1

- Your teacher will tell you how many weights to place on the trolley and on the weight carrier.

1 Write down the mass of the weight carrier for measurement 1 in table 2.

table 2 The measurements for Experiment 2.

measurement	mass of carrier (g)	force (N)	distance (m)	average time (s)	average speed (m/s)	final speed (m/s)	acceleration (m/s^2)
1							
2							
3							

- Place the trolley as far away as possible from the end point. This is the starting position. Measure the distance between the starting point and the end point.
- Measure how long it takes the trolley to reach the end of the air cushion track.
- Repeat this measurement two more times.

2 Determine the average time. Make a note of it in the table under 'Measurement 1'.

Measurement 2

- Move one weight from the trolley across to the weight carrier. The total mass (the carrier plus the trolley plus all the weights) does not change, but the driving force does.

3 Write down the mass of the weight carrier for measurement 2 in the table.

- Measure how long it takes the trolley to move from the starting point to the end of the air cushion track.
- Repeat this measurement two more times.

4 Determine the average time. Make a note of it in the table under 'Measurement 2'.

Measurement 3

- Move another weight from the trolley across to the weight carrier.

5 Write down the mass of the weight carrier for measurement 3 in the table.

- Measure how long it now takes the trolley to move from the starting point to the end of the air cushion track.
- Repeat this measurement two more times.

6 Determine the average time. Make a note of it in the table under 'Measurement 3'.

Writing up

7 Calculate the driving force for each measurement using $F_g = m \cdot g$. Note the results in the third column of the table.

8 Calculate the average speed for each measurement. Note the results in the sixth column of the table.

9 The final speed is 2× the average speed.
Calculate the final speed for each measurement. Note the results in the seventh column of the table.

10 Calculate the acceleration for each measurement. Note the results in the eighth column of the table.

11 Take a good look at your results. What can you say about the relationship between the resultant and the acceleration? Explain how you got your answer.

....

....

....

....

Your teacher will tell you whether or not you have to write up a report on this experiment.

EXPERIMENT 3 CARRYING OUT AN EXPERIMENT – THE ROLLING RESISTANCE OF A BICYCLE

45 minutes

Introduction

A sports scientist writing in a magazine for amateur racing cyclists states, “Many amateur racers do not realise how important the correct tyre pressure is. If the tyres are pumped up hard, you are quicker: a couple of bar more and the rolling resistance can be reduced by as much as 20%. In a time trial in a cycle race, the difference that can make could be several tens of seconds.”
You wonder whether this scientist is right and you decide to do an experiment.

Purpose

You are looking for an answer to the following research question:
How does the rolling resistance vary with the pressure in the bike tyres?

Requirements

For this experiment, you have to think up for yourself what practical equipment you will need.

Doing the experiment and writing it up

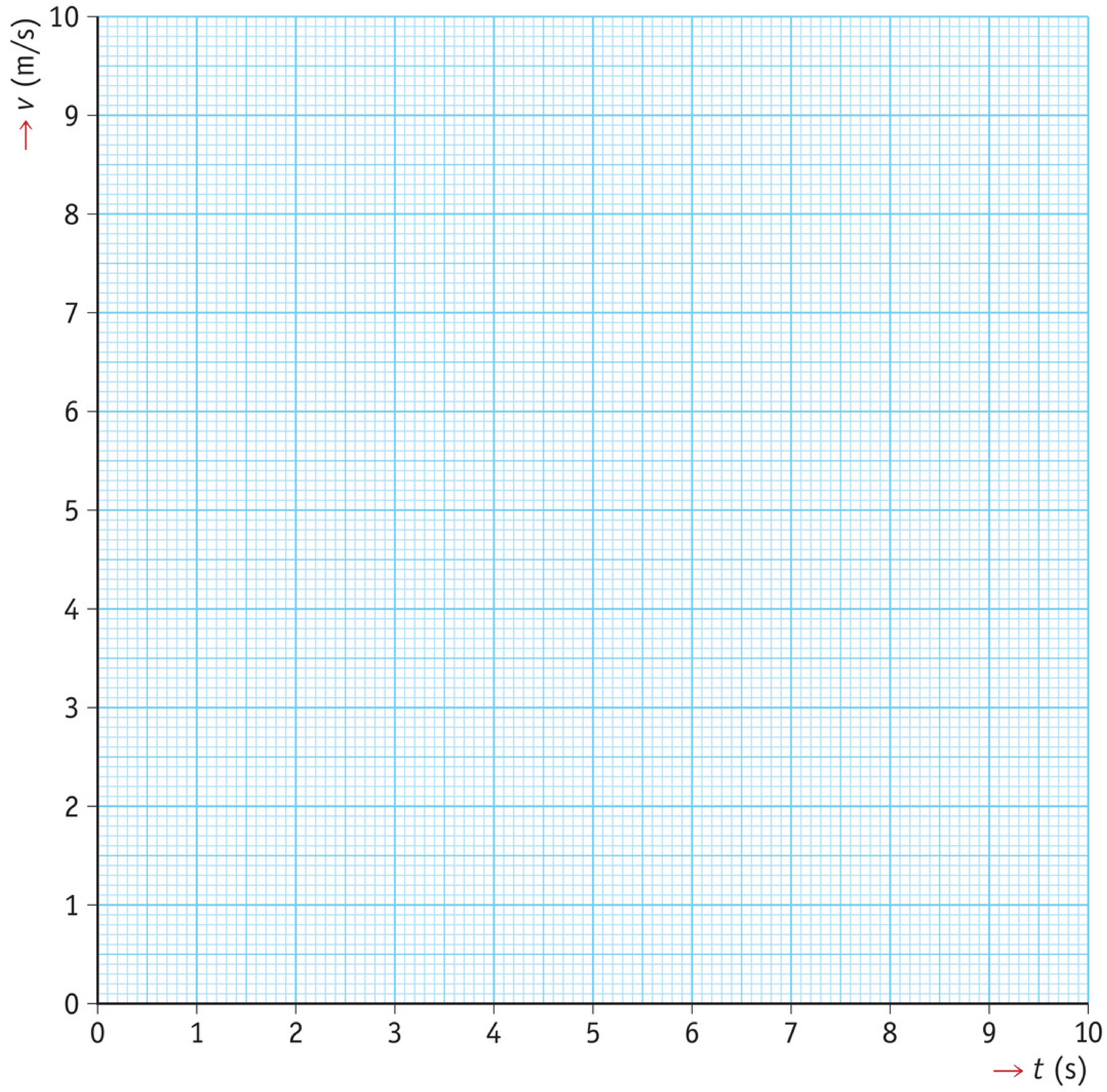
- Think about how you can give the most reliable answer to the question. What is your test setup going to look like; what exactly are you going to measure; how will you make sure that the measurements are repeatable (and can therefore be verified)? Tip: first think about how you can make the effect of air resistance on your measurements as small as possible.
- Talk it through together to discuss any risks that might be involved. What can you do to make sure that this experiment can be carried out safely?

1 Make a work plan for this study.

- The work plans will be discussed with the rest of the class in the next lesson. If necessary, you can make improvements to your own work plan.
- Then carry out the experiment.

2 Write down all the measurements, calculations and results.

3 Draw a graph of the rolling resistance against the pressure in the bike tyres.



4 Write down your conclusion.

....

....

....

....

Your teacher will tell you whether or not you have to write up a report on this experiment.

The following experiments can be found in the online learning environment. Your teacher decides which of these experiments will be done.

EXPERIMENT 4 AIR RESISTANCE AND SPEED

45 minutes

Introduction
You investigate how the air resistance varies with the speed of an object.

EXPERIMENT 5 DECELERATION IN CRASH TESTS

20 minutes

Introduction
You measure the average deceleration in crash tests using video measurement.

EXPERIMENT 6 CARRYING OUT AN INVESTIGATION: A SPRING-DRIVEN TOY CAR

45 minutes

Introduction
You investigate if a spring-powered toy car accelerates and decelerates uniformly when accelerating and decelerating respectively.



Working as a traffic manager

Waiting for a red traffic light. Go... stop... go... and then stop again for the next red light. For many car drivers, driving in a busy city is a daily torment. "If you're out of luck, you end up standing still more than you're actually moving!" For traffic managers, that irritation is seen as a challenge: how can we keep the traffic flowing better, without compromising safety?

In a densely populated country such as the Netherlands, it's easy for the traffic to become congested. During the rush hour in particular, the volume of traffic can be huge. Bottlenecks in the road network inevitably lead to major delays. The job of a traffic manager is to think up smart solutions for this. The more efficiently the traffic can be dealt with, the less long people will have to wait.

Plans for redesigning a road or crossroads can have a major impact. Thousands of road users – or sometimes many more than that – are affected and they all have an opinion about it. But you hardly ever hear anything about the people who develop the plans. All the more reason to go and talk to one of these planners. Traffic manager Aymee Prinsen (26) tells us about her work (figure 1).

How do you get to become a traffic manager?

"I've always found traffic interesting. All those people, moving around every day: what's the best way of arranging that? Puzzling away at a problem until you've got the best possible solution – that's something I simply enjoy. When I had to choose my next course after completing secondary education, I didn't take long to make up my mind. I knew that I wanted to do something with traffic.

name	Aymee Prinsen
age	26
education	secondary, science and technology profile
	vocational: *Built Environment* – traffic manager profile
job	traffic management advisor
plans	to start her own consulting agency in ten years' time



figure 1 Aymee Prinsen, a traffic manager.

> *"At school, it doesn't matter too much if you make the odd mistake in your calculations, but in traffic technology it does."*

After secondary school, I took the *Built Environment* course at vocational college. You were able to choose from a variety of professional fields and graduation profiles there. And with my interest in traffic, I automatically ended up with mobility as the main field. I chose traffic management for my graduation profile, because I'm mainly interested in the technological side and I like solving concrete problems.

The course was very much practically oriented. You learn how to design a road, lay out crossroads and make sure that the urban traffic stays on track. You get theoretical courses too, but you're busy with projects for most of the time. Then you work with a group of other students on a task for an external customer like a town council, who want to improve traffic safety at a crossroads."

So what does your work involve?

"After the vocational course, I got a job as an advisor in a medium-sized consultancy bureau. There are about twenty people there, five of them involved with traffic technology. I work on projects there such as optimising the layout of crossroads with traffic lights.

A project like that starts with me talking to a potential customer. If our agency gets the job, I first make a design. For instance, I'll calculate how long the traffic lights have to be green and in what sequence, and how long the traffic then gets to clear the conflict zone – that's the jargon term for the area where the traffic flows cross (figure 2).

Once the design is complete, I convert it into a computer program than turns the traffic lights on and off. I write that program in a programming language called Visual C and test it using traffic simulation software.

During the installation of the traffic lights, I monitor everything on behalf of the town council to check that the plans are being implemented correctly. Once everything's there and the programs have been installed, the system is tested once again. And then it's opened. That's always a tense moment, because you don't want anything to go wrong then, of course."

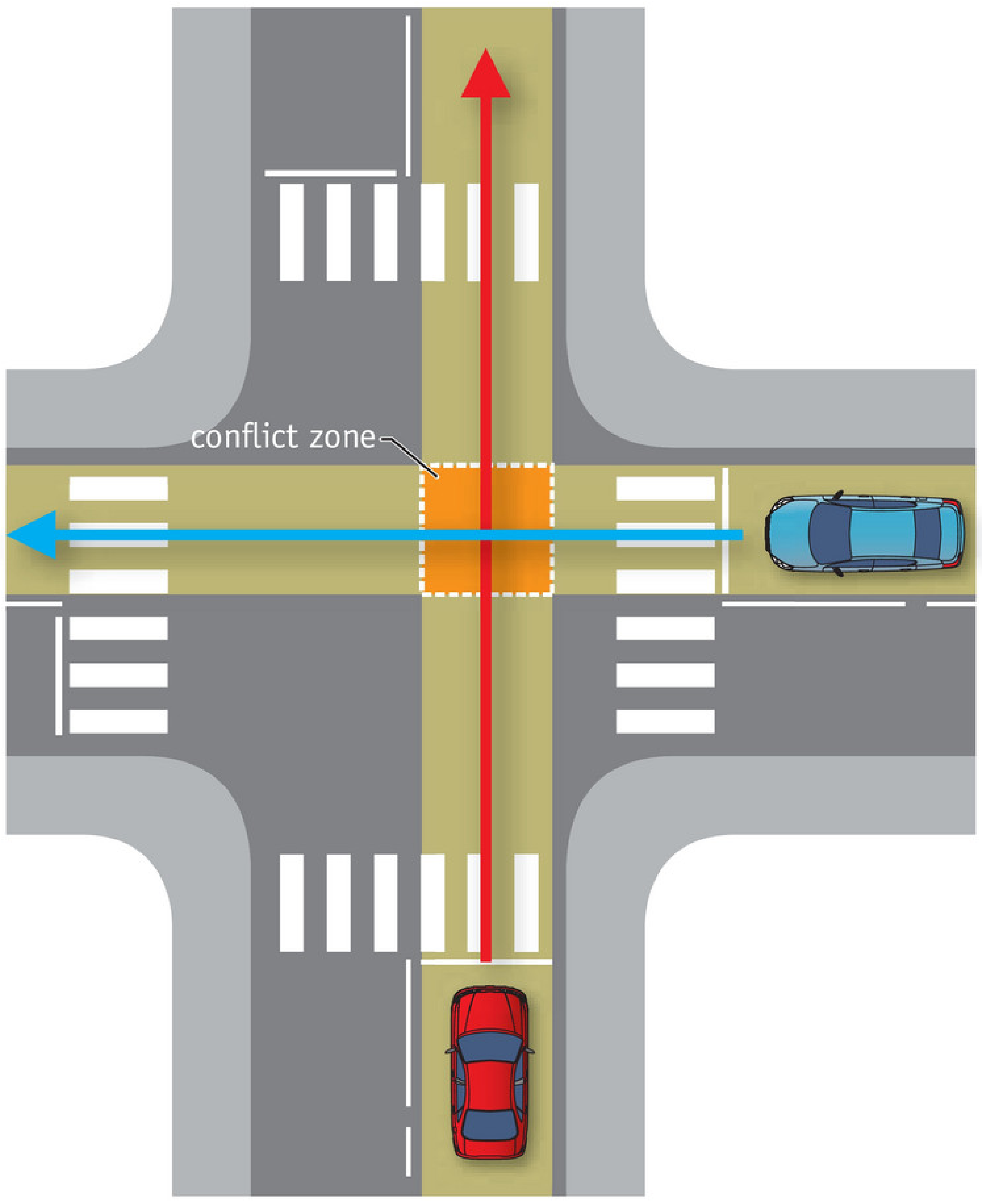


figure 2 Two cars approaching a conflict zone.

What role does physics play in your professional field?

"When a traffic light goes orange, it takes a little while before the conflict zone is clear and traffic from another direction can drive across it. That's called the clearance time. As a traffic expert, you sometimes do have to calculate the clearance time, because it's different for every crossroads and for each type of road user.

You calculate the clearance time using the familiar physics formulas about speed and distance. I often use a computer to calculate things, but I do also do calculations on a piece of paper, with a calculator. It's another way of convincing myself that everything is correct.

At school, it doesn't matter too much if you make the odd mistake in your calculations, but in traffic technology it does. If you make a traffic light turn green too soon, it can cause accidents. Fortunately, you usually do find the errors during testing, but there's always a risk. On top of that, correcting an error in the software costs a lot of time and money."

Is your work challenging enough?

"Oh yes – definitely. Like any other company, we have to keep on innovating. Ideas about traffic flow and safety are always changing, and we have to move with the times. A good example is the norm for green at a set of traffic lights. During my training, for example, I was taught that you must never give two directions green lights at the same time: if one direction has green, the directions crossing it must have red.

Everyone actually knew perfectly well that this rule was too strict. Sometimes, driving up from where you have stopped up to the conflict zone can take a long time, whereas leaving the conflict zone can be very quick. You then end up with a negative clearance time: the conflict zone is empty before you need it to start emptying. There is now a brand new approach called 'intergreen' that makes use of that extra time. It allows the traffic lights for direction A to turn green while they are still green for direction B for a few moments (figure 3)."

Intergreen only makes a couple of seconds' difference per cycle, but that can add up to quite a bit over the course of the whole day. And intergreen is probably good for traffic safety too, because people are then less likely to run a red light. That's currently being studied. Whatever: when intergreen is applied throughout the Netherlands soon, an agency like ours has to be ready for it. Because every second that we can trim off the waiting times is a second gained."

The effect of intergreen

In 2014, the consultancy agency Grontmij and the Directorate-General for Public Works and Water Management studied the effectiveness of intergreen. The study showed that the number of vehicle-hours lost at crossroads was reduced by an average of 3.6% if intergreen was used. Over the Netherlands as a whole, that would save 4.9 million hours of time that vehicles lose while waiting every year.

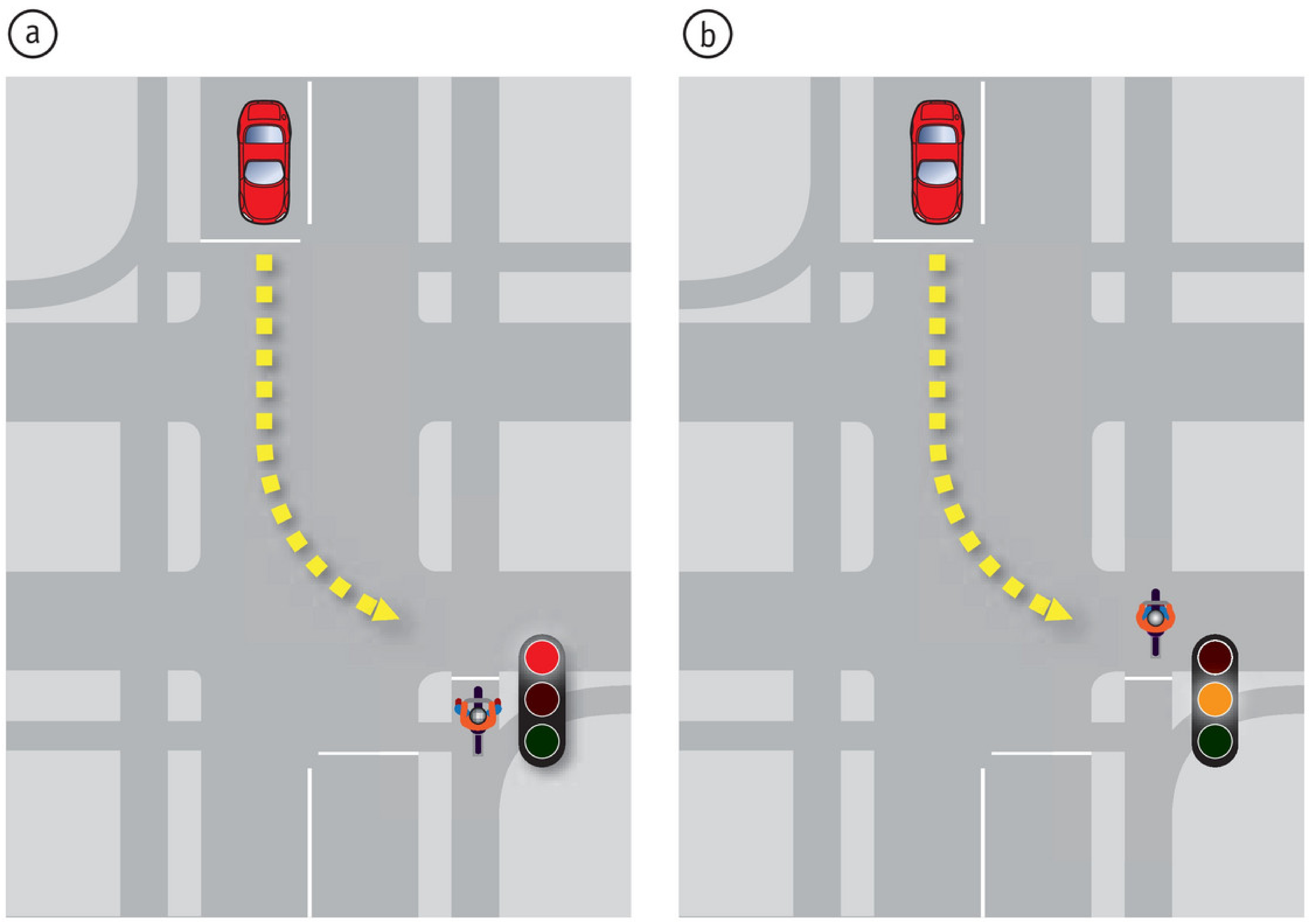


figure 3 Waiting unnecessarily (a) or driving through with intergreen (b).

EXERCISES

1

When a traffic light turns red, it takes a little while before the last car has left the conflict zone. The time this takes is called the clearance time (or exit time). The clearance time is calculated using the formula:

$$t_{af} = \frac{d + l}{v_{af}}$$

a Use figure 4 to explain what the letters *d* and *l* mean.
b Explain why it is important to include *l* in the formula.
c How big is *l* for a car? And for a bus? Make an estimate.

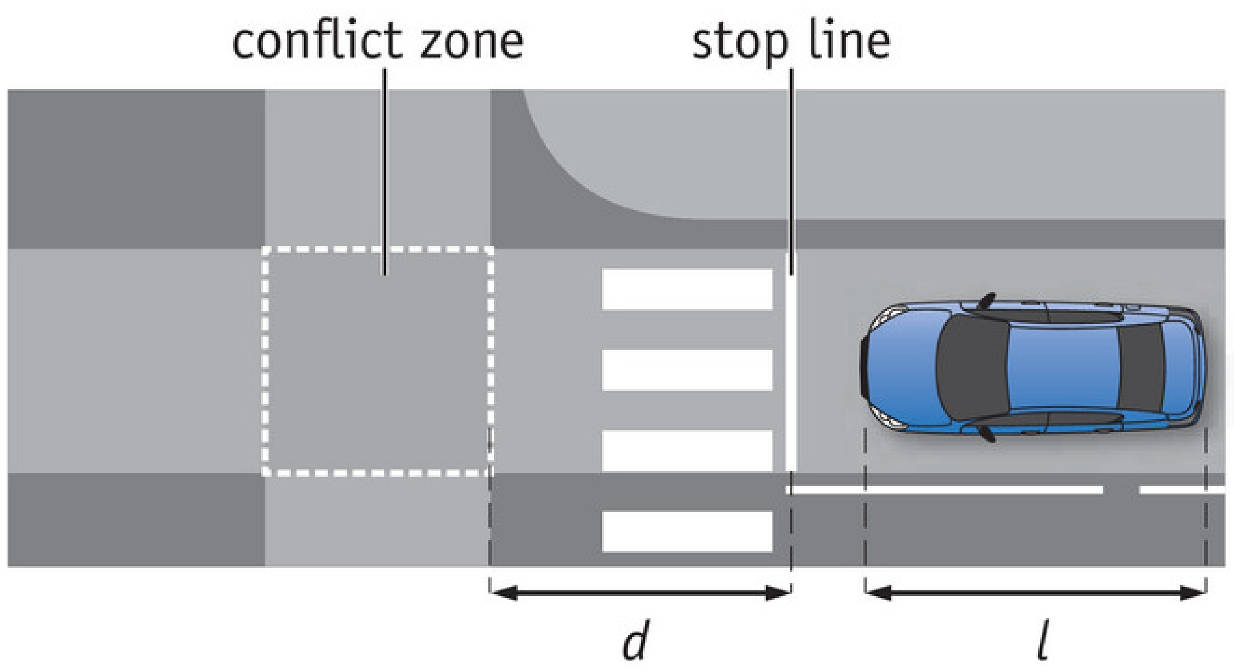


figure 4 A car approaches the conflict zone.

2

When a traffic light turns green, it takes a little while before the first car enters the conflict zone. The time this takes is called the entry time. The entry time is calculated using the formula:

$$t_{in} = \frac{d}{v_{in}}$$

a What does the speed v_{in} mean?
b Explain why *l* does not appear in this formula.
c The formula assumes a steady entry speed. This is not the case in reality. Does this make the entry time longer or shorter?
d In Germany, the light first goes orange before switching to green. Explain what effect this has on the entry time.

3

Figure 5 shows you two roads for one-way traffic. The distances from the stop line to the conflict zone are not equal. The light switches to red at B at the same moment the light at A switches to green.

a Explain why the conflict zone is then empty for an unnecessarily long time.

b The article states that the clearance time t_{clear} is negative.
Suggest a formula for t_{clear}.

c Explain why there is a risk of collision if the light at B switches to green the same time the light switches to red at A.

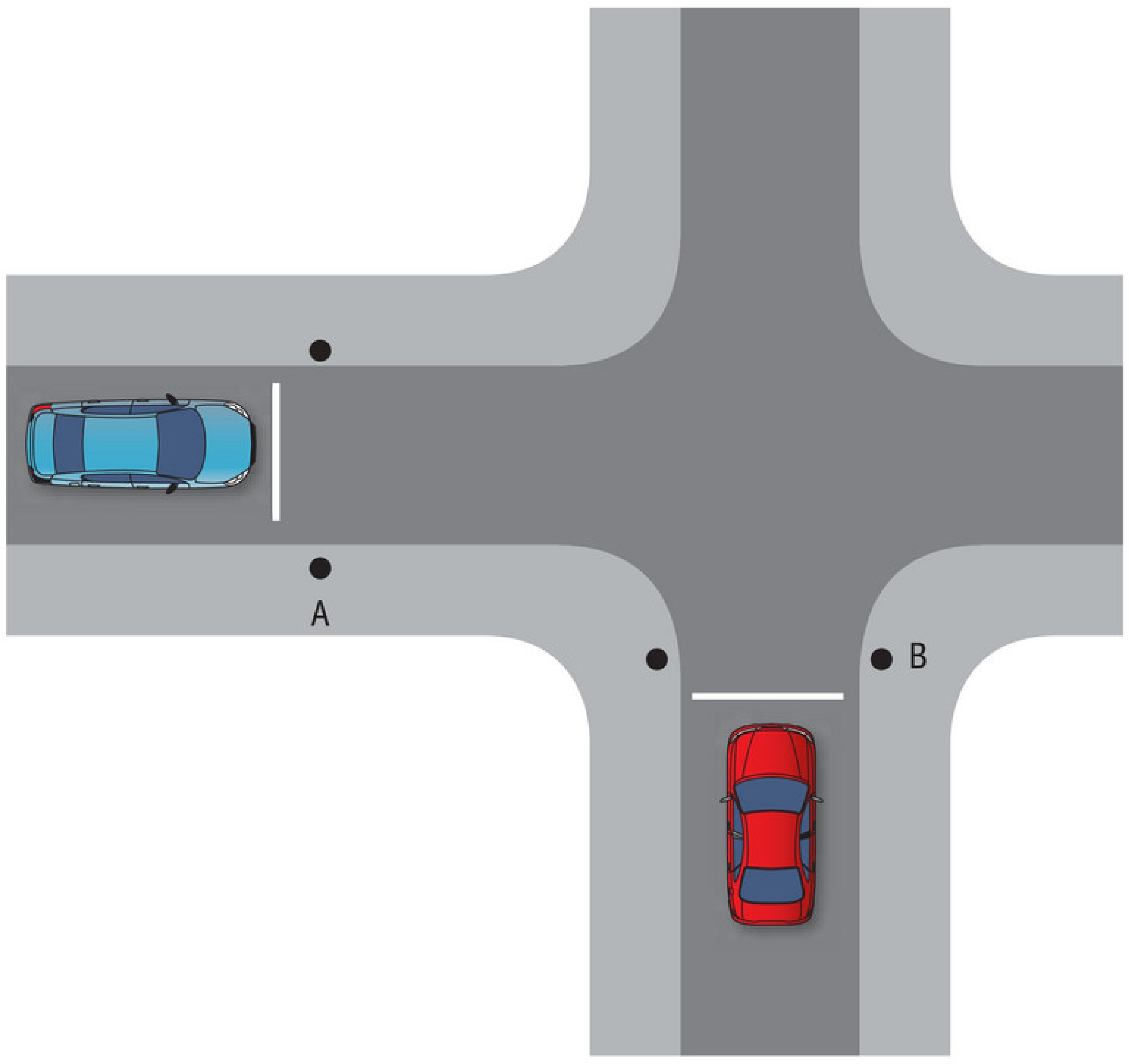


figure 5 Two roads for one-way traffic.

4

A traffic light system is converted to intergreen.
Explain why cyclists should be given extra warnings against ignoring a red light.

★ 5

Search the Internet for information about intergreen. Write a short piece of text (one A4) explaining what intergreen is about and what its benefits and disadvantages are.
Your teacher will tell you how this exercise is checked and assessed.

Course material overview

4.1 ACCELERATING AND DECELERATING

REMEMBER

- To make a graph of a motion in a (v,t) diagram, you draw the speed at each measured time as a dot. You then draw a straight line or a curve that fits the points as well as possible.
- In a (v,t) diagram, an upward straight line corresponds to a uniform acceleration, a downward straight line to a uniform deceleration and a horizontal straight line to a uniform motion.
- You can also record the motion in an (x,t) diagram. Here you draw the location at each measured time. In this diagram, a parabolic curve corresponds to an accelerated motion and a slanted line to a uniform motion.
- A uniform acceleration tells you by how many m/s the speed increases each second.
- You calculate the acceleration using the formula $a = \frac{\Delta v}{\Delta t}$
- In an acceleration a is a positive number and in a deceleration a is a negative number.
- You can determine the distance covered from a (v,t) diagram by reading the area under the graph.

CONCEPTS

acceleration
The increase in speed per second.

acceleration (accelerating motion)
A movement in which the speed keeps increasing.

deceleration
The reduction in speed per second.

(displacement, time) diagram
A graph showing the position against the time taken. This is also called an (x,t) diagram.

(speed, time) diagram
A graph showing the speed against the time taken. this is also called a (v,t) diagram.

uniform acceleration
A movement in which the speed is increasing at a steady rate.

uniform deceleration
A movement in which the speed is decreasing at a steady rate.

uniform motion
A movement in which the speed remains constant (does not change).

(v,t) diagram
A graph showing the speed against the time taken. This is also called a (speed, time) diagram.

(x,t) diagram
A graph showing the position against the time taken. This is also called a (displacement, time) diagram.

4.2 FORCE, MASS AND ACCELERATION

REMEMBER

- Inertia means that the speed or direction of an object does not change unless a resultant force acts on it.
- Objects with a large mass have a lot of inertia. This means it is difficult (and takes a long time) to make their speed or direction change.
- You can calculate the amount of force required to give an object a certain acceleration using the formula $F_{res} = m \cdot a$
- If only gravity is acting on an object, that object is in free fall. On Earth, this can only occur with objects that fall in a container that has been pumped to a vacuum.
- The acceleration due to gravity on the Earth is 9.8 m/s^2. The acceleration due to gravity is represented using the symbol *g*. You can calculate the gravitational force acting on an object using the formula $F_g = m \cdot g$

CONCEPTS

acceleration due to gravity
The acceleration (9.8 m/s^2) with which objects move towards the Earth in free fall.

free fall
A situation where only gravity is acting on an object.

inertia
The degree to which an object can change speed or direction. Objects with a large mass have a lot of inertia and can change speed and direction less easily.

Newton's Second Law
The formula $F = m \cdot a$

4.3 FORCES AND WORK

REMEMBER

- A vehicle on Earth always needs a driving force to move. That is because there are always resistance forces that act against the motion.
- A vehicle needs energy to be able to move. The vehicle only uses part of this energy usefully. The engine uses that proportion to do work. That means that the engine produces a force that drives the vehicle forward over a certain distance. Work is not a form of energy, but a process in which energy is converted.
- You can calculate the work using the formula $W = F \cdot s$
- The unit of work m is the same as the unit of energy, the joule J. 1 Nm = 1 J.
- You can calculate the efficiency of an engine by entering the work carried out as E_{used} in the formula $\eta = \frac{E_{used}}{E_{tot}} \cdot 100\%$

CONCEPTS

work
The amount of energy that an engine uses usefully to move a mass over a certain distance.

4.4 BRAKING AND COLLISIONS

REMEMBER

- You can calculate the stopping distance using the formula *stopping distance = reaction distance + braking distance*
- You can determine the stopping distance in a (v,t) diagram by reading the area under the curve.
- You increase the collision time with a crumple zone, seatbelts, airbags and crash helmet, which reduces the braking forces.
- You increase the surface area using a seatbelt and crash helmet, which reduces the pressure on the body during a collision.
- You calculate the pressure with the formula $p = \frac{F}{A}$

CONCEPTS

braking distance
The distance covered by a vehicle while braking.

crumple zone
The parts at the front and back of a car that are designed to collapse if it is involved in a collision.

pressure
The force an object exerts on the ground per unit area.

reaction distance
The distance covered by a vehicle during the reaction time.

reaction time
The time between seeing the hazard and the brakes being applied.

Go to the *Flash cards* and the *Diagnostic test*.

5 Circuits

AUTOMATIC CONTROL

A lot of devices have circuits that can detect something and respond to it. The circuit can let the device perform tasks independently, such as opening the gates at a railway station, selling soft drinks, raising an alarm, controlling the temperature or turning on a light.

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What do you already know about circuits?

LEARNING OBJECTIVES

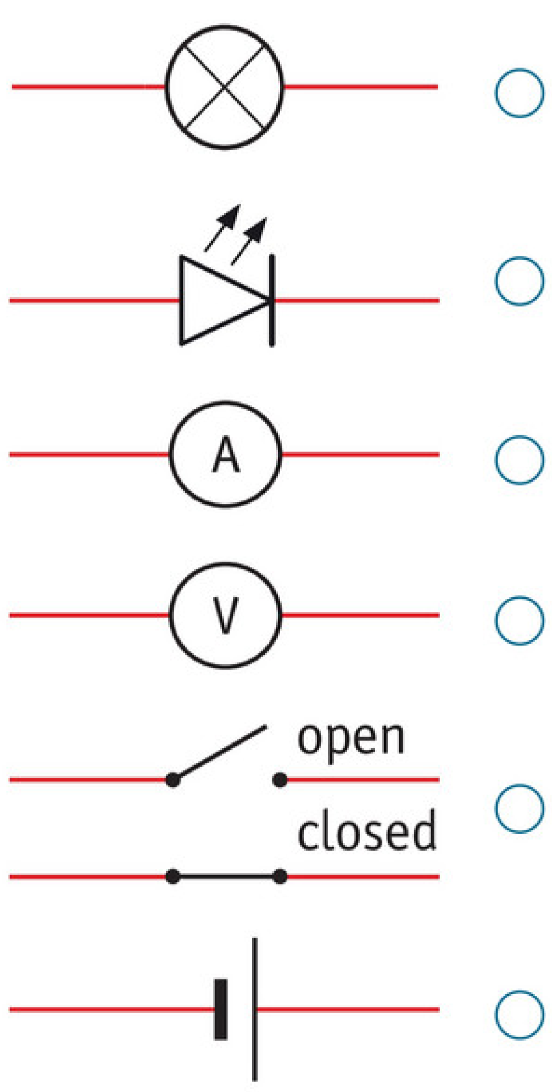
1. You know the symbols that you use to make a circuit diagram.
2. You can list some applications of infrared radiation.
3. You can explain what voltages and currents are and how you measure these variables.
4. You can explain the difference between a parallel circuit and a series circuit.

In Parts 1 and 2 of Nova NaSk and in Chapter 1 of this school year, you learned a few things about electricity. You will need this knowledge when you start this chapter. If you want to do a quick check of what you can remember, do the following exercises.

EXERCISES TESTING YOUR PRIOR KNOWLEDGE

1 Connect the correct component to each symbol.

A
B
C
D
E
F



1 battery
2 light source
3 LED
4 switch
5 voltmeter
6 ammeter

2 Underline the types of radiation that the human eye can see.
IR radiation – light – UV radiation

3 You can measure the voltage across a wire with a voltmeter and you can measure the current through a wire with an ammeter.
In figure 1, draw the symbols for the two meters in the correct places.

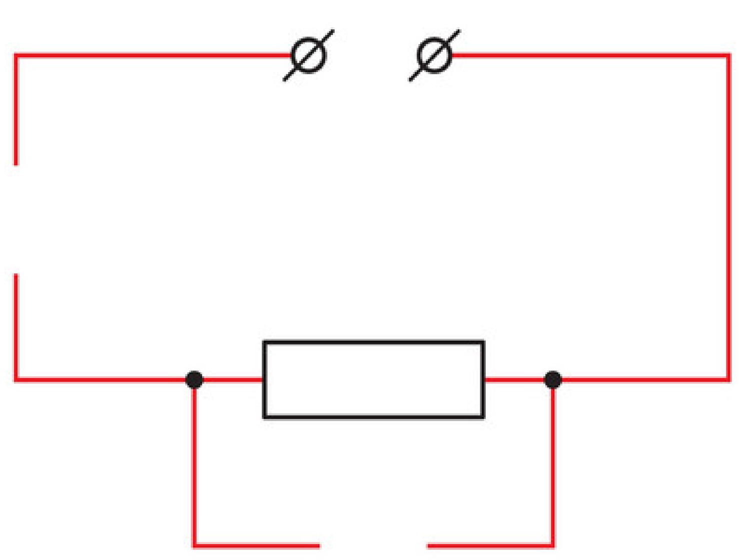


figure 1 A voltmeter and an ammeter in a circuit.

4

In a parallel circuit, the *voltage* / *current* is divided over all the branches. In this circuit, the *voltage* / *current* is the same for all branches.
In a series circuit, the *voltage* / *current* is the same throughout the circuit. In this case, the *voltage* / *current* is divided over the different circuit components.

If you want to know whether you have enough prior knowledge for this chapter, you can take the online *Prior knowledge test*. You can also find videos about the key learning objectives for this chapter there.

1 Charge and voltage

LEARNING OBJECTIVES

5.1.1 You can describe how you can give an electrically neutral object made of Perspex or PVC an electric charge.
5.1.2 You can explain how to tell the difference between a positive charge and a negative charge.
5.1.3 You can explain what role electrons play when an object is charged and discharged.
5.1.4 You can describe two ways of discharging an object that has been charged.
5.1.5 You can explain what voltage sources are used in daily life.
5.1.6 You can do calculations with the formula $Q = I \cdot t$.
PLUS 5.1.7 You can do calculations with the elementary charge of the electron and the proton.

When you take off a fleece sweater on a dry winter day, you may hear it crackling softly. In the dark, you may even see sparks jumping across. The sparks are discharges of static electricity: not dangerous under normal conditions, but still not very pleasant if the current runs through your body.

CHARGING OBJECTS

If you rub a woollen cloth on a PVC pipe, the pipe will then attract paper shreds. A fine stream of water is also attracted by the tube. We say that the PVC tube has become **electrically** or **statically charged** as a result of being rubbed.



figure 1 Polystyrene balls are attracted by a comb that has been charged by rubbing.

You can tell that an object is charged because it attracts other objects (figure 1). You can see this, because a lot of dust collects on the object, for example. Sparks may jump across to other objects too. You can hear this (as a soft crackling sound) and sometimes see or feel it.

A charged object mostly loses its charge quickly. The more water vapour is in the air, the more quickly the object discharges. That is why experiments with charged objects work best if the air is very dry.

POSITIVE AND NEGATIVE CHARGES

If you rub a silk cloth firmly over a Perspex rod, the rod will become charged. The same thing happens if you rub a PVC tube with a woollen cloth. However, there is a difference between the charges that were given to the two objects. Two charged Perspex rods repel each other. The same goes for two charged PVC pipes. But a charged Perspex rod and a charged PVC pipe attract each other.

You can repeat these experiments using objects and cloths that are made of different materials. You will then soon realise that there are two kinds of charge. Objects that have the same charge repel each other. Objects that have different charges attract each other.

One type of **charge** is called **positive** (plus) and the other type is called **negative** (minus). A Perspex rod that has been rubbed with a silk cloth has a positive charge. A PVC tube that has been rubbed with a woollen cloth has a negative charge. Two positives repel each other, as do two negatives, but plus and minus attract each other (figure 2).

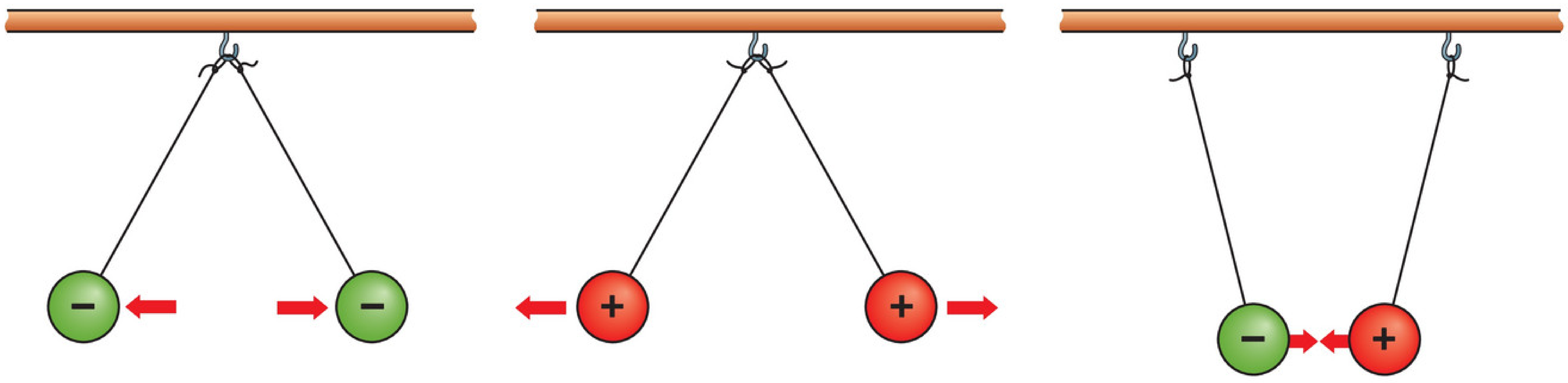


figure 2 Attraction and repulsion.

ELECTRONS

An uncharged object contains exactly the same amount of positive charge and negative charge. You therefore do not notice that such an object contains any charges. We say that it is **neutral** (electrically). You can give some objects an electric charge by rubbing them with a cloth. Physicists have discovered that small, negatively charged particles 'jump' from the cloth to the object or the other way round. These particles are called **electrons**.

There are two options now (figure 3):

- The electrons go from the cloth to the object. The object then has a surplus of electrons. It is negatively charged overall. The opposite applies to the cloth: it has lost electrons so it is now positively charged.
- The electrons go from the object to the cloth. The opposite happens then. The object loses electrons and becomes positively charged. The cloth gets extra electrons and becomes negatively charged.

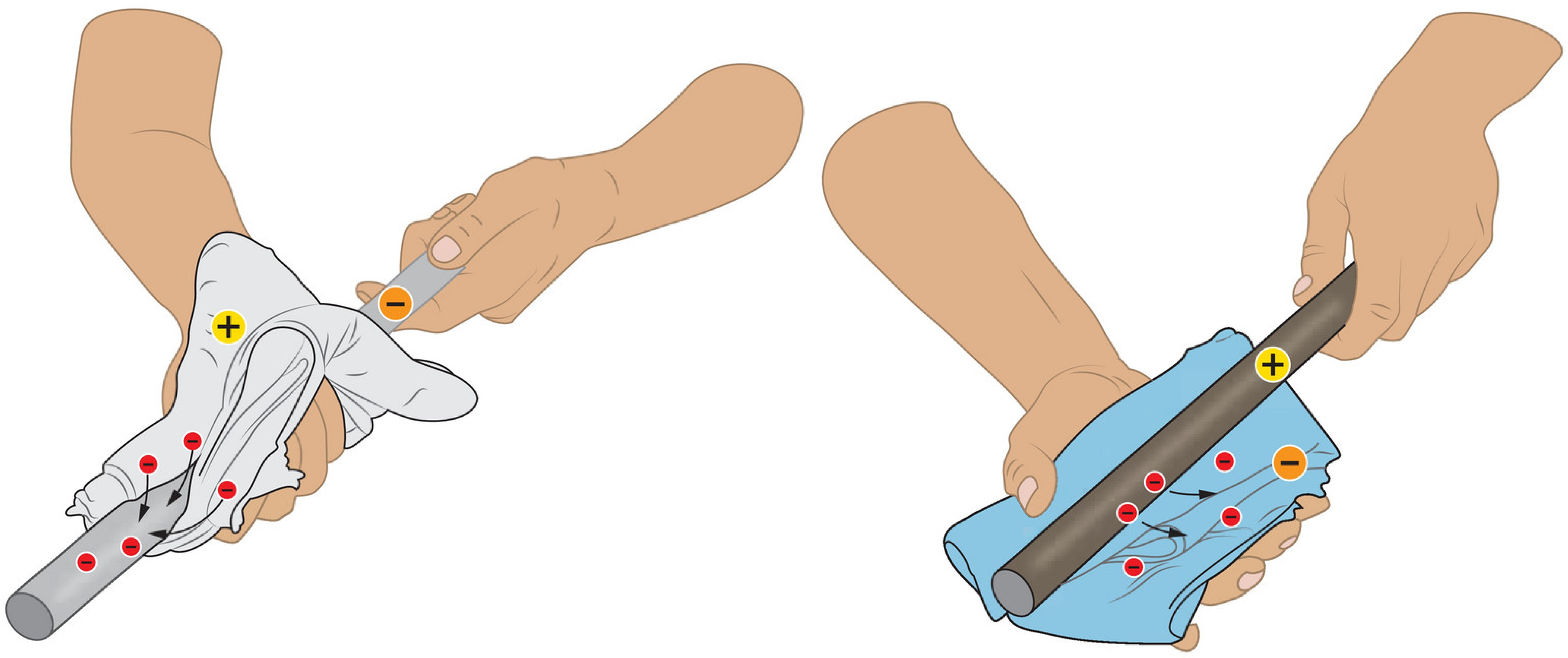


figure 3 Rubbing makes electrons move.

An object's positive charge is also due to particles. These particles are called **protons**. Protons can't move from their position in a solid. That means they can't move from one object to another. So when you rub an object, you are always moving electrons with a negative charge around (and never protons with a positive charge).

DISCHARGING A VOLTAGE

Figure 4 shows two equally large metal balls on plastic stands. Ball A is negatively charged and ball B is positively charged. In such a case, we say that there is a **voltage** between A and B. When you make a conducting connection between A and B, electrons start to move from A to B. There is then an electric current.

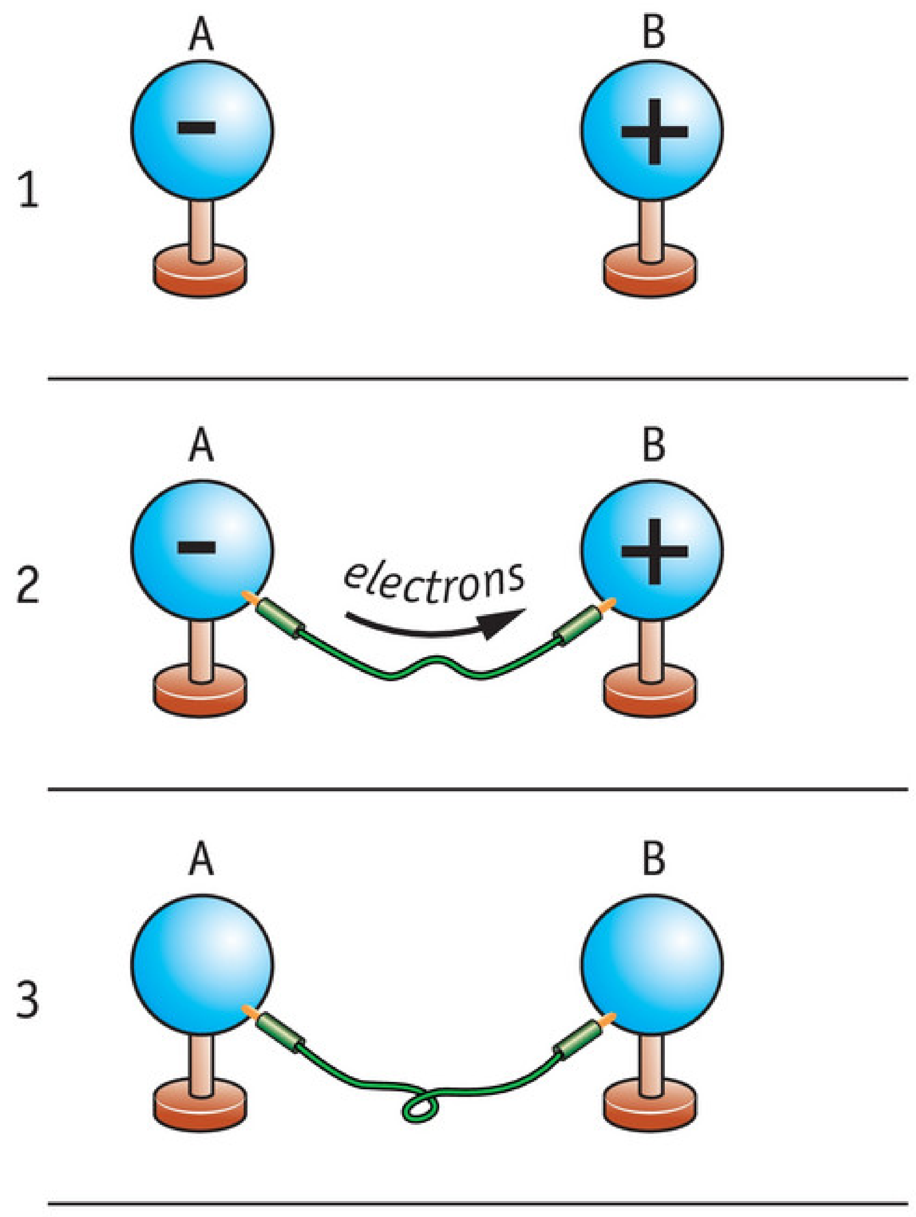


figure 4 Electrons move from minus to plus.

The current between A and B only flows for a very short while. This is because there will very soon be no voltage between A and B anymore; both balls then have the same charge. A charged object can also discharge when a spark jumps across to something (or someone) else. This also only lasts for a moment: the charged object loses its charge in just a fraction of a second.

If there is a high voltage between a charged object and its environment, sparks may jump across. For instance, the outside of a car can build up a voltage of up to 3000 V while driving along. You notice that when you get out of the car: you feel a shock as the car discharges through your body. A shock like that is not dangerous because the current is small and only flows through your body for a moment.

You can use a static electricity generator to generate a static charge with a high voltage (figure 5). But a machine like that discharges again very quickly. It is not much use for practical purposes. What you need in practice is a voltage source that can produce a current for a long period with a constant voltage. That is why we use dynamos and batteries in daily life.



figure 5 This large static electricity generator is in Teylers Museum in Haarlem.

CHARGE AND CURRENT

When a current of 1 amp flows through a wire, $6.2 \cdot 10^{18}$ electrons move across a cross-section of that wire every second (figure 6). Even though each individual electron only has a tiny charge, that vast number of them produces a big enough charge for use in practical applications.

The unit of charge, the coulomb (with the symbol C) is based on the amp and the second. This unit is named after the French researcher Charles-Augustin Coulomb (1736–1806). A current of 1 amp transports 1 coulomb of electrical charge in 1 second (measured at a cross-section of the conductor). You could also say: 1 coulomb is equal to the charge of $6.2 \cdot 10^{18}$ electrons.

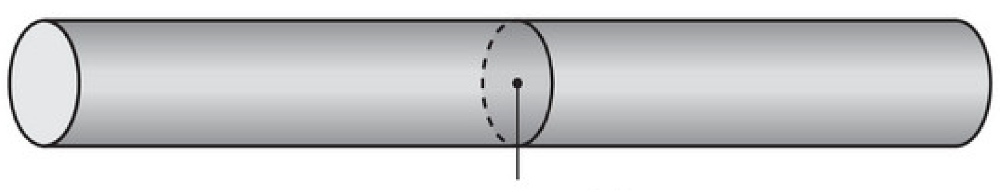


figure 6 A wire is a long, thin cylinder with a circular cross-section.

The total charge that flows through a wire depends on the current and the time. The relationship is given by the formula

$$Q = I \cdot t$$

where:

- Q is the charge in coulombs (C);
- I is the current in amps (A);
- t is the time in seconds (s).

PLUS THE ELEMENTARY CHARGE

Like its mass, the charge is a fundamental property of a material. That becomes clear when you look at the atoms that make up all materials. Figure 7 shows a simplified representation of an atom of the metal lithium. Like all atoms, a lithium atom consists of a positively charged nucleus with a cloud of negatively charged electrons around it. The nucleus in turn is made up of protons and neutrons.

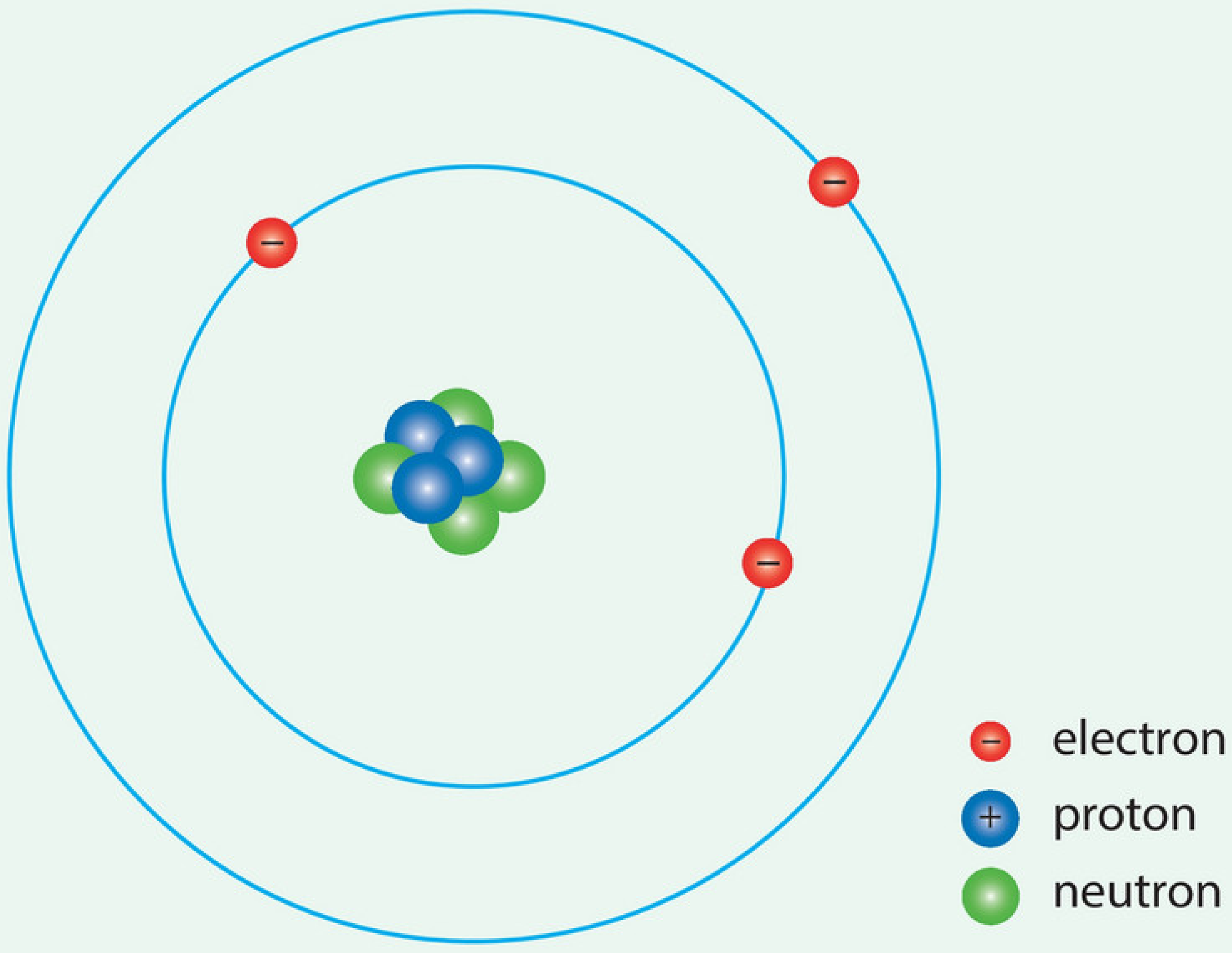


figure 7 A model of a lithium atom (atomic number 3).

As you can see in table 1, the charge on an electron is tiny: $-1.6 \cdot 10^{-19}$ C. This charge is negative. A proton has a positive charge of the same size: $+1.6 \cdot 10^{-19}$ C. These are the smallest amounts of charge that can be found in nature. We often say that the elementary charge is $1.6 \cdot 10^{-19}$ C. You then need to remember that this charge is negative for electrons and positive for protons. An atom has as many protons as electrons. That is why an atom is electrically neutral as a whole.

table 1 Some properties of the particles in an atom.

particle	charge (coulombs)	mass (kg)
proton	$+1.6 \cdot 10^{-19}$	$1.7 \cdot 10^{-27}$
neutron	0	$1.7 \cdot 10^{-27}$
electron	$-1.6 \cdot 10^{-19}$	$9.1 \cdot 10^{-31}$

In metals, the outermost electrons in an atom can easily move from one atom to the next (figure 8). These electrons are called 'free electrons' for that reason. If you connect a metal object to a battery, the free electrons all start moving in one direction, from the battery's negative terminal to its positive terminal: a current flows. All metals are therefore conductors. Other materials do not have free electrons and are therefore insulators.

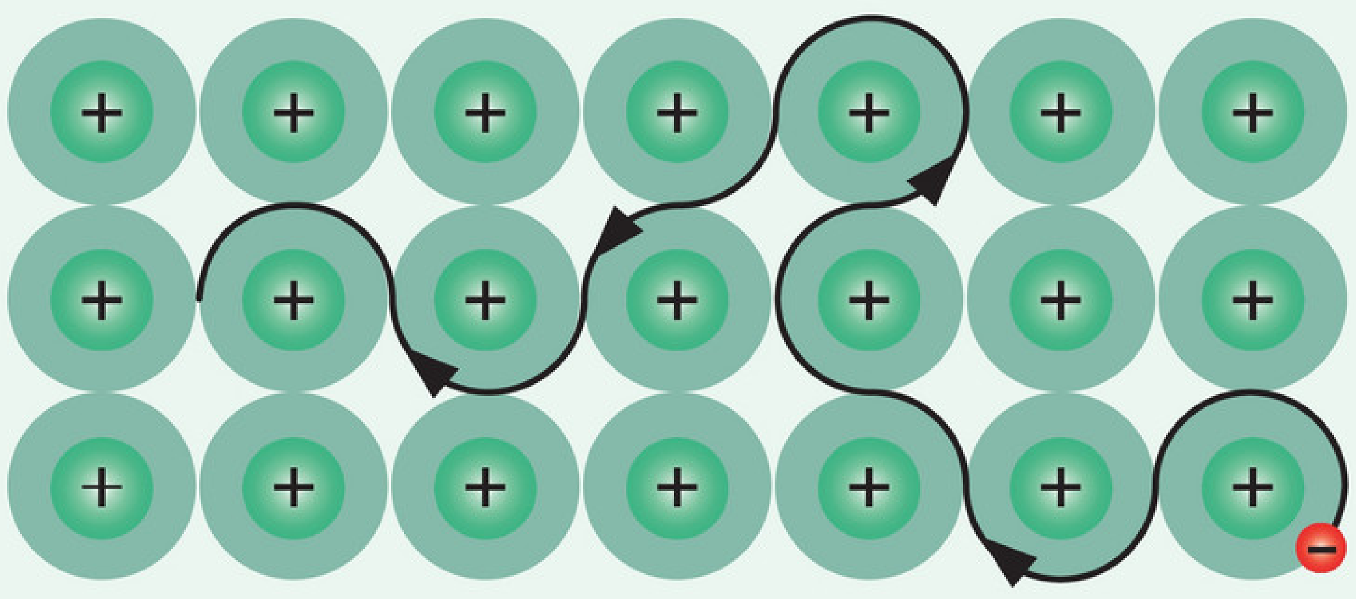


figure 8 This is how free electrons move through a metal grid.

EXAMPLE EXERCISE 1

In an experiment with static electricity, two electrically charged balls are connected to each other. In 10 ms, $7.5 \cdot 10^{12}$ free electrons move from one ball to the other.
Calculate the average current.

given $Q = 7.5 \cdot 10^{12} \times -1.6 \cdot 10^{-19}\ \text{C} = -1.2 \cdot 10^{-6}\ \text{C}$
$t = 10\ \text{ms} = 0.010\ \text{s}$

required $I = ?$

working $I = \frac{Q}{t} = \frac{-1.2 \cdot 10^{-6}}{0.010} = -1.2 \cdot 10^{-4}\ \text{A} = -0.12\ \text{mA}$

The minus sign tells us the direction of the current. The direction is often not important and so the minus sign is left out.

Practice the concepts using the *Flash cards*.

COURSE MATERIAL

1 You can charge a PVC tube negatively by rubbing it with a woollen cloth.
- **a** Explain why the tube becomes charged.
- **b** The particles that jump across from one object to the other are called ....
- **c** These particles move *from the tube to the cloth* / *from the cloth to the tube*.
- **d** Why can't the positive particles jump across?

2 Answer the following questions.
- **a** How can you tell when an object is electrically charged (with static electricity)?
- **b** What do you know about the amount of charge in a neutral object?
- **c** Why do you sometimes feel a shock when you get out of a car after a ride in it?

IN PRACTICE

3 The air humidity is low in clear, freezing weather. You may then notice very clearly that objects get charged electrically by friction (rubbing).
In what way (or ways) might you notice:
- **a** that your hair and comb get charged when you comb your hair?
- **b** that a fleece sweater has become charged when you take it off?
- **c** that a strip of sticky tape gets charged when you pull it from the roll?

4 In a demonstration experiment, Diana holds onto a static electricity generator (figure 9).
- **a** What is a static electricity generator for?
- **b** Explain what is happening to Diana's hair in figure 9.
- **c** Diana is standing on an insulating surface.
  Explain why this is needed.
- **d** In this experiment, the voltage can get as high as 10 kV but it is still not dangerous.
  Explain why, and what makes it different from the mains voltage.



figure 9 Diana holds onto a Van de Graaff generator (a kind of static electricity generator).

5

During a flight, a plane can become charged by the forces of resistance from the air.

a Explain why the electrical charge could be a hazard when the plane is being refuelled after landing.

b Why is the risk of an accident greatest in winter, particularly when it is freezing at the airport?

c Why do you have to connect the plane to the tank truck first with a metal earthing cable first before refuelling (figure 10)?

d Explain why the driver has to wear highly insulating gloves when connecting the cable.



figure 10 The driver of the tanker unrolling the earthing cable.

6

Figure 11 shows an electroscope. You can use this device to check if an object is charged. If you touch the button with a charged object, the two pieces of silver paper move apart.

a Explain why this can happen.

b Explain whether you can tell from the result of the electroscope test if the object is positively or negatively charged.

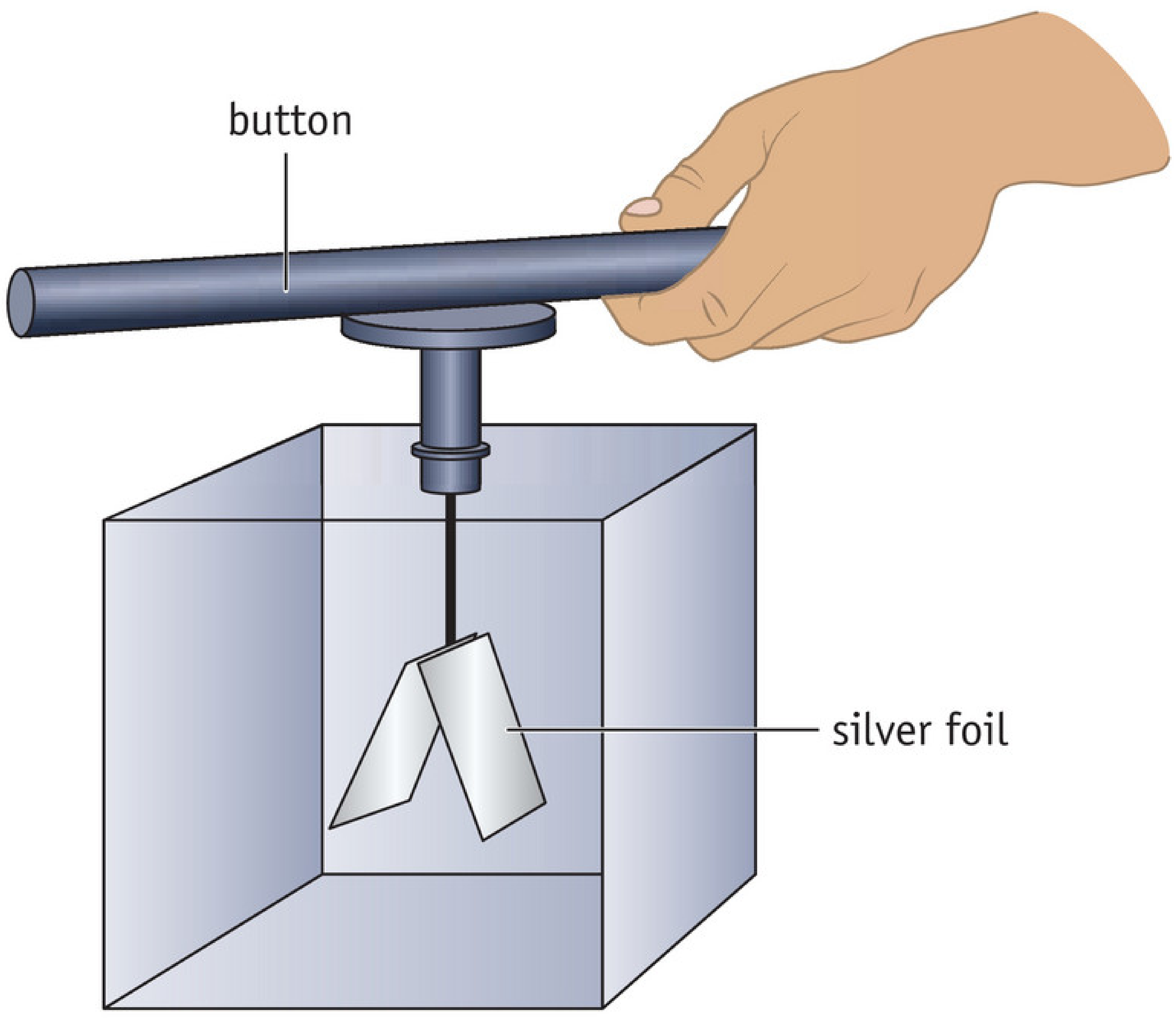


figure 11 An electroscope.

7

Mary connects the button of a positively charged electroscope A to an equally strong negatively charged electroscope B using a conducting wire.

a What happens to the results of both electroscopes?

b Describe what has happened after the two electroscopes have been connected.

8 There is a big difference in voltage between the underside of a thundercloud and the ground.

a Give two reasons why the combination of a thundercloud plus ground is not a suitable voltage source for practical applications.

b The upper side of a thundercloud is positively charged and the underside negatively charged (figure 12).
Explain why the earth's surface under the cloud becomes positively charged.

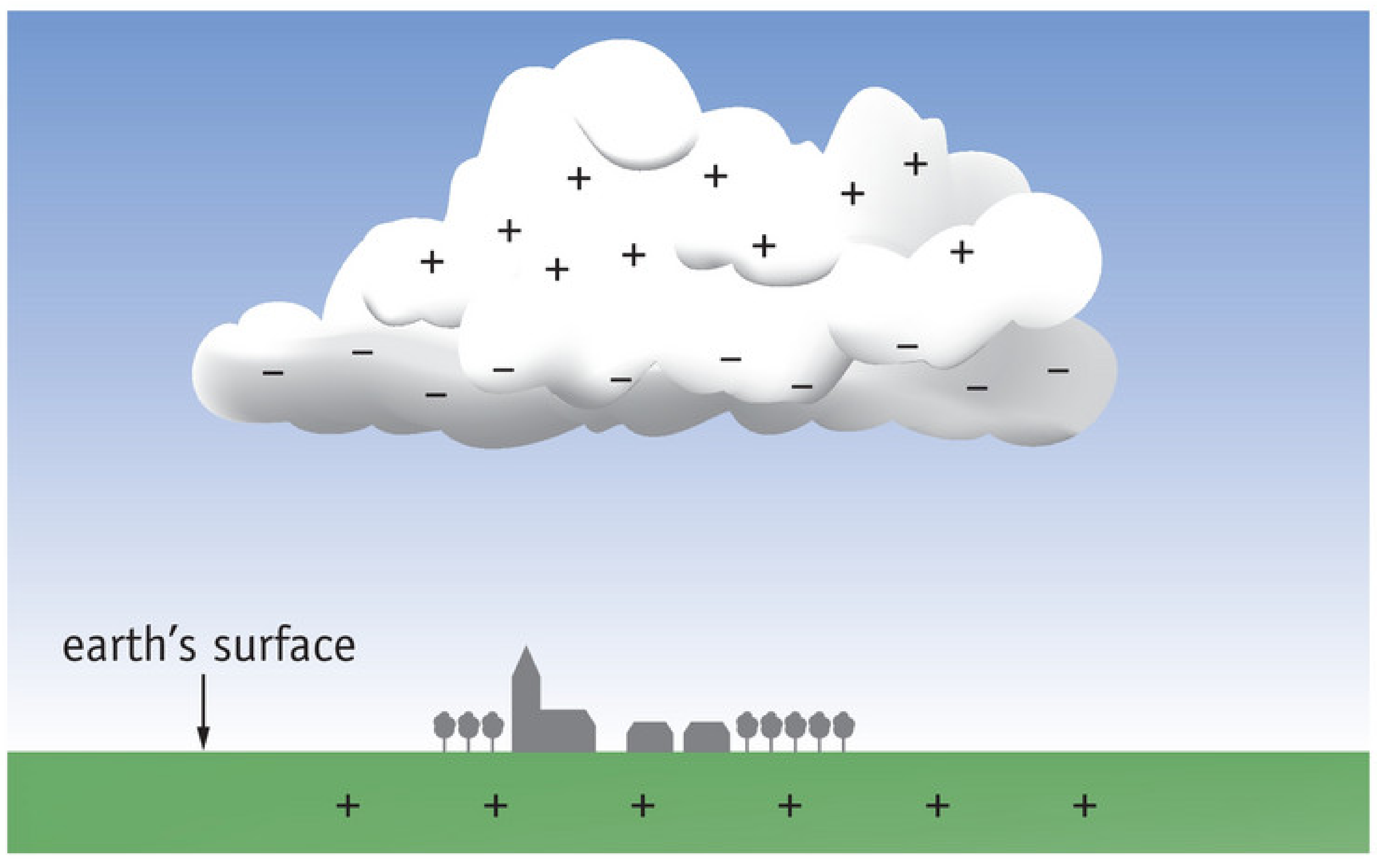


figure 12 The distribution of charges in a thundercloud.

★ 9 An AA battery produces a current of 50 mA for 40 hours. After that, it is 'flat', which means it can no longer produce enough voltage.

a How much electrical charge has flowed out of the battery during that time?

b Calculate how long the same type of AA battery could produce a current of 10 mA for.

Test what you know with *Test yourself.*

PLUS THE ELEMENTARY CHARGE

10 Ions are charged atoms with a surplus or shortage of electrons. There are various types of copper ion, including the ion Cu^{2+}.

a Explain whether this copper ion has a shortage of electrons or a surplus.

b Calculate the size of the charge on a Cu^{2+} ion.

c A copper ball has free electrons in the metal lattice of its copper atoms. The ball contains $4.0 \cdot 10^{24}$ copper atoms, each of which has two free electrons. Emma gives the (insulated) ball a charge of +3.0 mC. Calculate what percentage of the free electrons in the ball have gone.

11 Arrest squads in the Netherlands sometimes use a stun gun, also known as a taser. When the police use a taser, two wires are shot at the suspect (figure 13). The taser has a voltage source that makes a current flow through the wires. The voltage is high but because the current is only 2.1 mA, the shock is painful but not dangerous for the suspect.

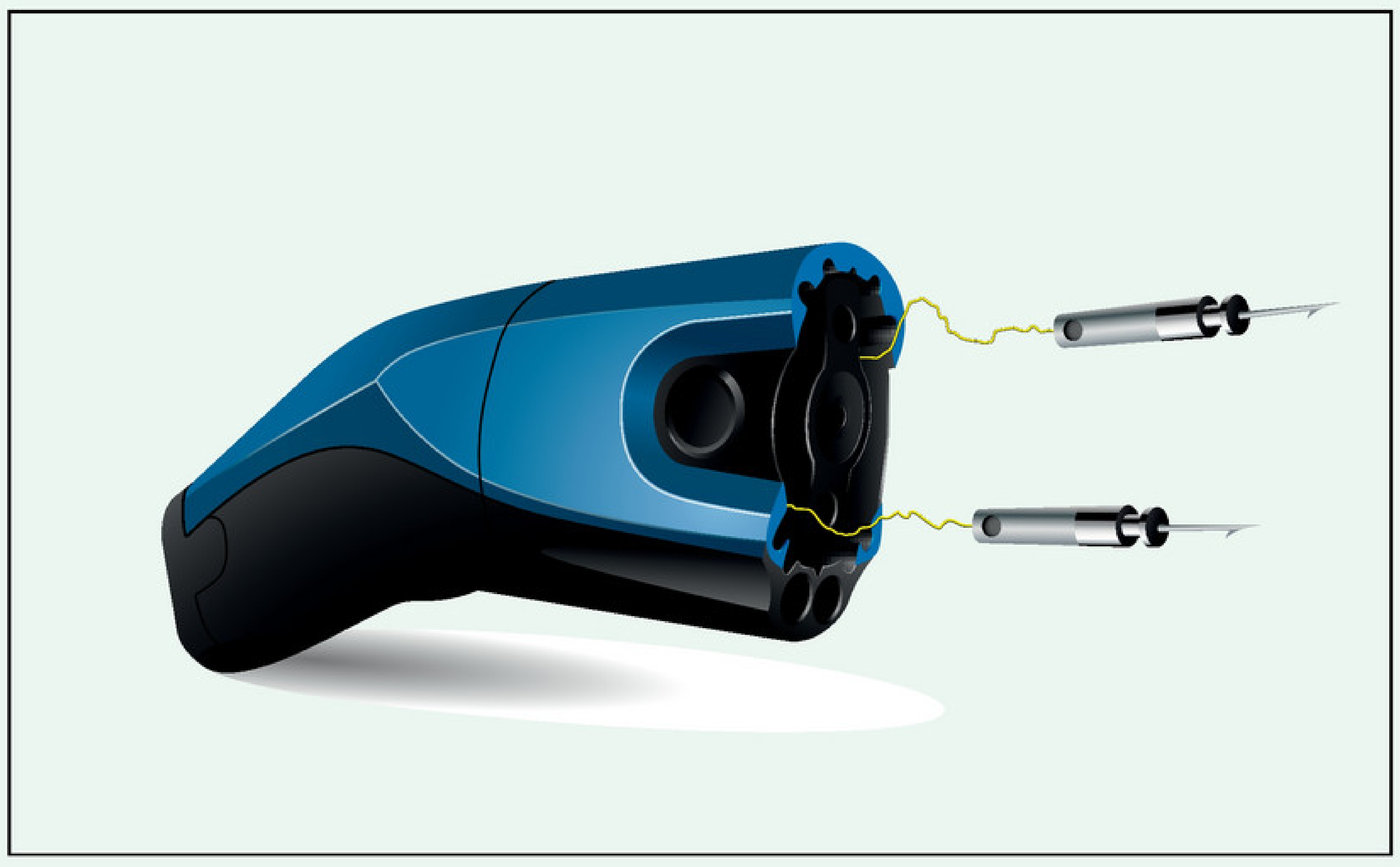


figure 13 When the police use a taser, two wires are fired at the suspect.

a Make a sketch of the circuit that is described above.

figure 14 Circuit when a taser is fired.

b Calculate how many seconds a shock from the taser lasts if $4.6 \cdot 10^{16}$ electrons flow through the suspect.

c Explain why a taser is not dangerous for the suspect even though it has such a high voltage.

2 Resistance

LEARNING OBJECTIVES

5.2.1 You can explain how to determine the resistance of a wire or other component.
5.2.2 You can do calculations using the relationship between resistance, voltage and current.
5.2.3 You can explain the difference between ohmic and non-ohmic resistance.
5.2.4 You can describe how the resistance of an NTC or LDR depends on other variables.
5.2.5 You can explain how to set the desired resistance on an adjustable resistor.
PLUS 5.2.6 You can use the specific resistivity to calculate the resistance of a wire.

There are all kinds of appliances in your home that work on 230 V mains voltage. The amount of current that runs through those appliances can vary a great deal. The current through a tumble dryer, for instance, is much greater than the current through a light bulb. It would seem that there is less resistance to the flow of electrons in the tumble dryer.

CALCULATING THE RESISTANCE

The setup in figure 1 lets you measure the relationship between the voltage *across* a wire and the current *through* the wire. The 'voltage across a wire' means the voltage between the two ends of the wire. Figure 2 shows the diagram for the circuit.



figure 1 How to determine the resistance of a wire.

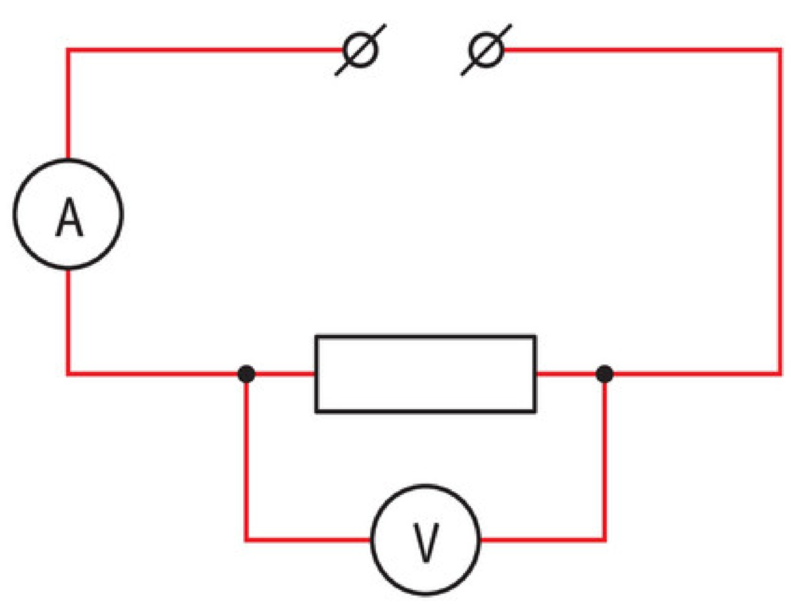


figure 2 The circuit diagram for the circuit in figure 1.

If you carry out this experiment with various wires, you will notice that the differences are large: some wires need a high voltage to 'force' a small current through the wire. A wire like this has a high **resistance**: it is difficult for current to flow through it. There are also wires where a low voltage creates a large current. These wires have a low resistance: it is easy for current to flow through them.

You can therefore define the resistance of a circuit component using the voltage (*across* the component) and the current (*through* the component). According to that definition, the resistance is equal to the voltage divided by the current. This gives you a useful numeric value for the resistance. Expressed as a formula:

$$R = \frac{U}{I}$$

where:
- R is the resistance in ohms (Ω);
- U is the voltage in volts (V);
- I is the current in amps (A).

The unit of resistance is named after the German physicist Georg Simon Ohm (1789–1854).

EXAMPLE EXERCISE 1

The packaging for a light bulb says 12 V/50 mA.
Calculate the resistance in kilohms (kΩ) if the bulb is lit at the correct voltage.

given $U = 12$ V
$I = 50$ mA $= 0.050$ A

required $R = ?$

working $R = \frac{U}{I} = \frac{12}{0.050} = 2.4 \cdot 10^2\ \Omega = 0.24\ \text{k}\Omega$

OHM'S LAW

EXP. 1

You can use the setup in figure 1 to carry out a series of measurements in which you increase the voltage more and more. The results of such an experiment are drawn in figure 3. The experiment uses a wire of a metal called constantan (an alloy of copper, nickel and manganese). In the graph, the current has been plotted against the voltage. Such a graph is called an **(I,U) diagram**.

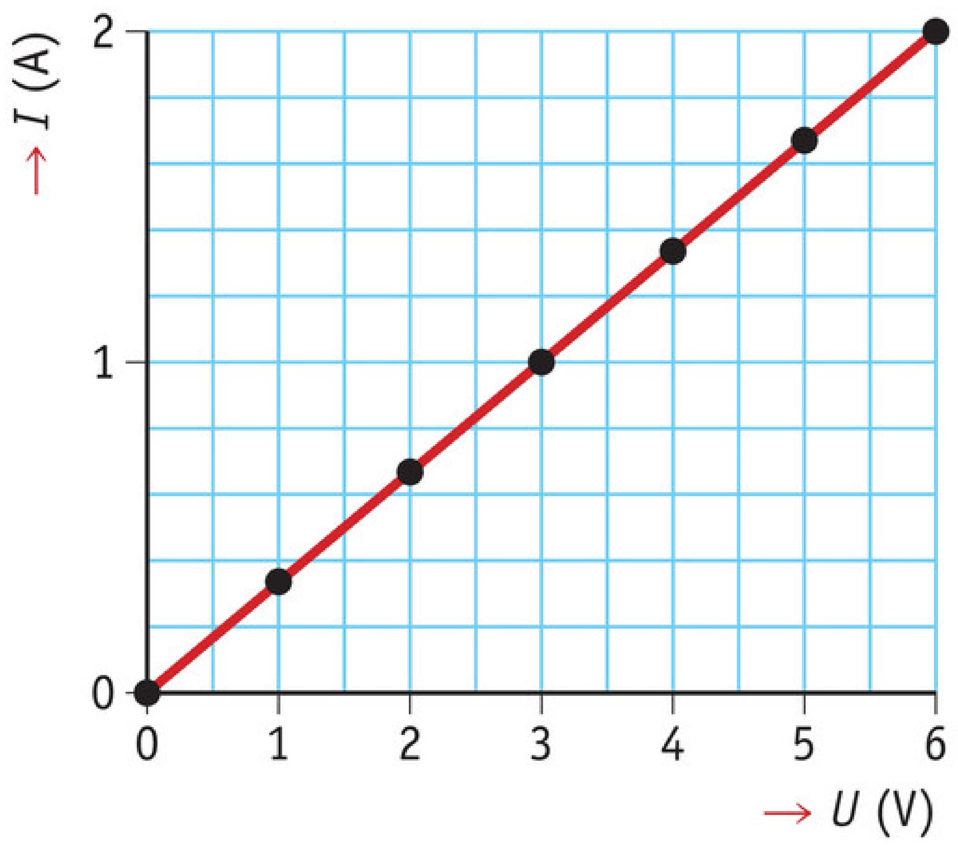


figure 3 The (I,U) diagram of a constantan wire.

You see
- If the voltage doubles, the current will be doubled too.
- If the voltage triples, the current will become be tripled too.
- and so forth.

In other words,

> The voltage (across the wire) and the current (through the wire) are directly proportional.

This rule is called **Ohm's Law**.

Ohm's Law shows that the wire's resistance has a constant value: if you divide the voltage *U* by the current *I*, you always get the same number. So the resistance *R* is the same whatever the value of the current. We call a resistance like that an **ohmic resistance**.

RESISTANCE AND TEMPERATURE

EXP. 2

If you repeat this experiment with an incandescent lightbulb, you get a different result. You can see that in the (*I*,*U*) diagram in figure 4. The voltage and the current are not directly proportional any longer: when the voltage is doubled, the current clearly lags behind. The resistance is therefore increasing. You can also see that if you calculate the resistance for every point with the formula. In that case, Ohm's law does not apply.

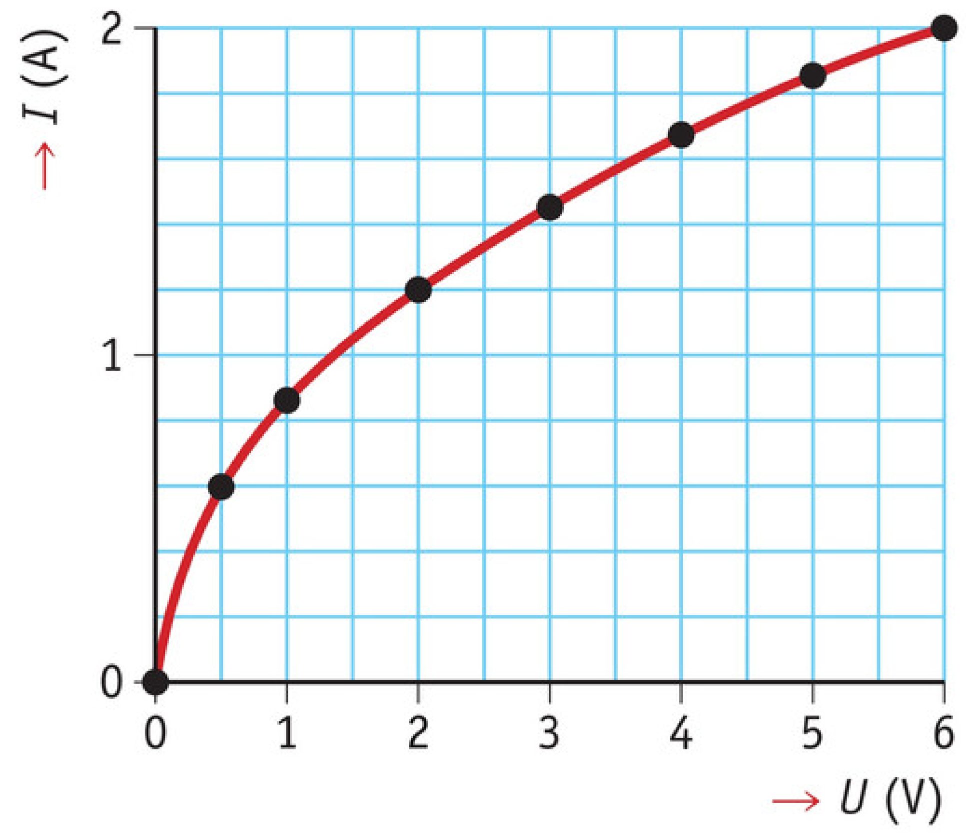


figure 4 The (*I*,*U*) diagram of an incandescent bulb.

The fact that the resistance increases has to do with the temperature. As the voltage across the filament increases, the bulb will light up more and more brightly. The temperature of the filament rises a lot, up to as much as 2500 °C. The resistance of the filament increases significantly at such high temperatures.

Almost all types of wires have a higher resistance when their temperature increases. Constantan wires are an exception: their resistance is constant, even when they become hot. Even so, you can often assume that other wires have a constant resistance too. If the temperature rise is limited (which is the case in many applications) then you can ignore the increase in resistance.

VARIABLE RESISTORS

Circuits sometimes use components with variable resistance. Two examples are the **NTC** and the **LDR**.

- An NTC (figure 5) is sensitive to changes in temperature. As the temperature of an NTC increases, its resistance becomes lower. The NTC will conduct much better then and pass more current.
- An LDR (figure 6) is sensitive to changes in the amount of light. If more light falls on an LDR, its resistance will be lower. The LDR will conduct much better then and pass more current.

These variable resistors are widely used in automatic circuits: the NTC as a temperature sensor and the LDR as a light sensor.

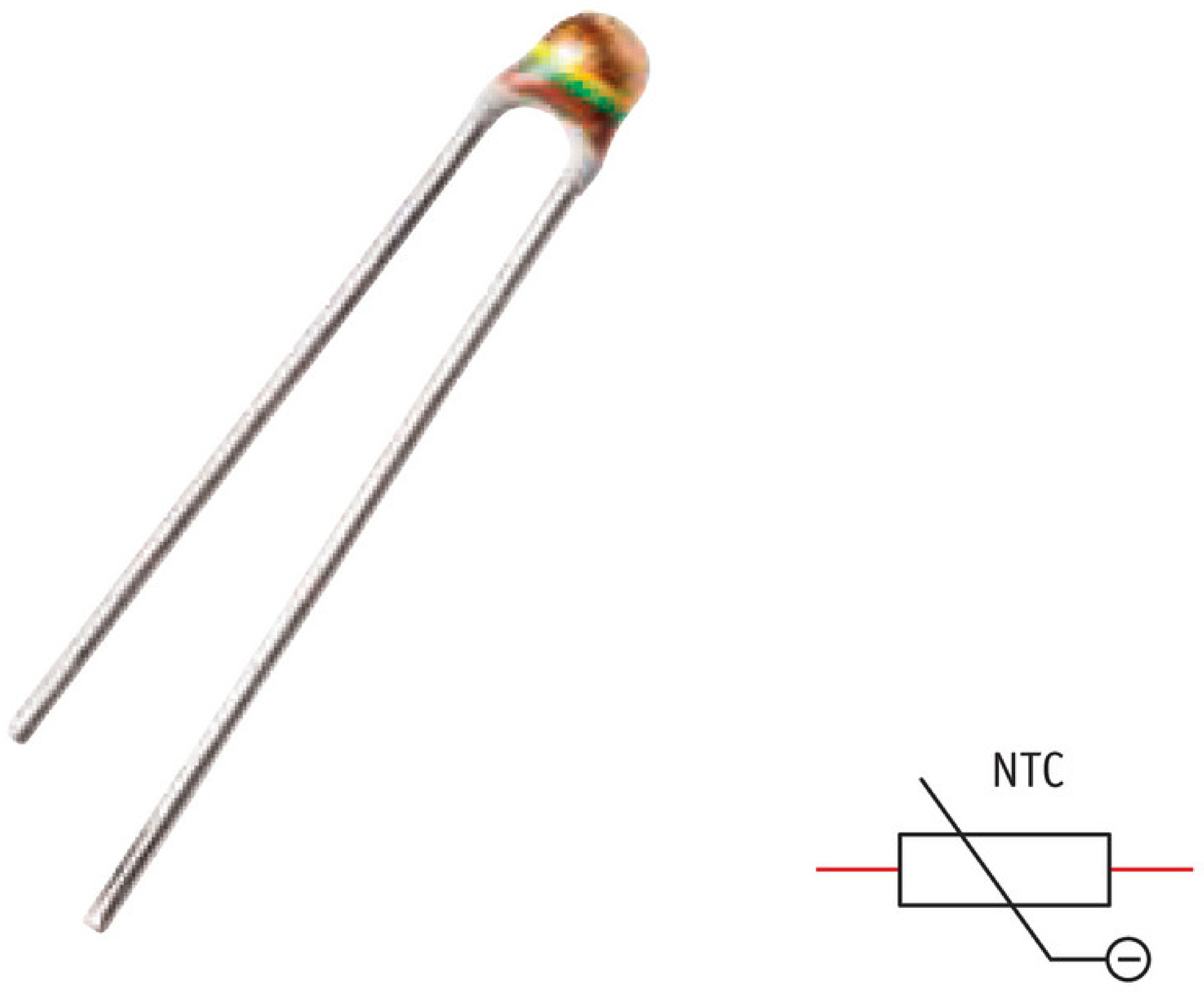


figure 5 An NTC with its circuit symbol.

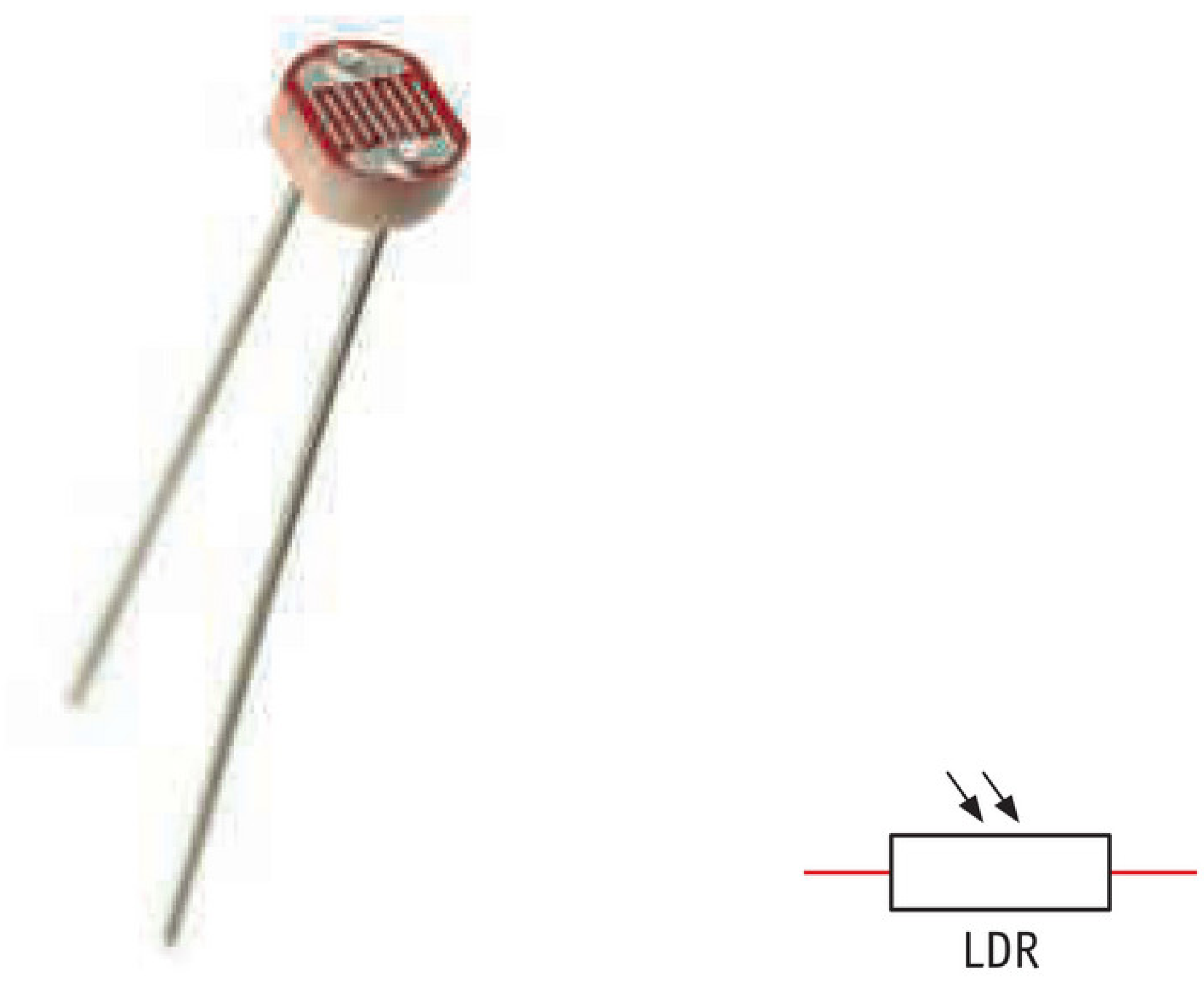


figure 6 An LDR with its circuit symbol.

Another commonly used component is the variable resistor. It consists of a long, rolled-up wire. You use a slider to control which part of the wire becomes part of the circuit (figure 7). The shorter you make that part, the smaller the resistance. That lets you set the resistance to be the value you need.

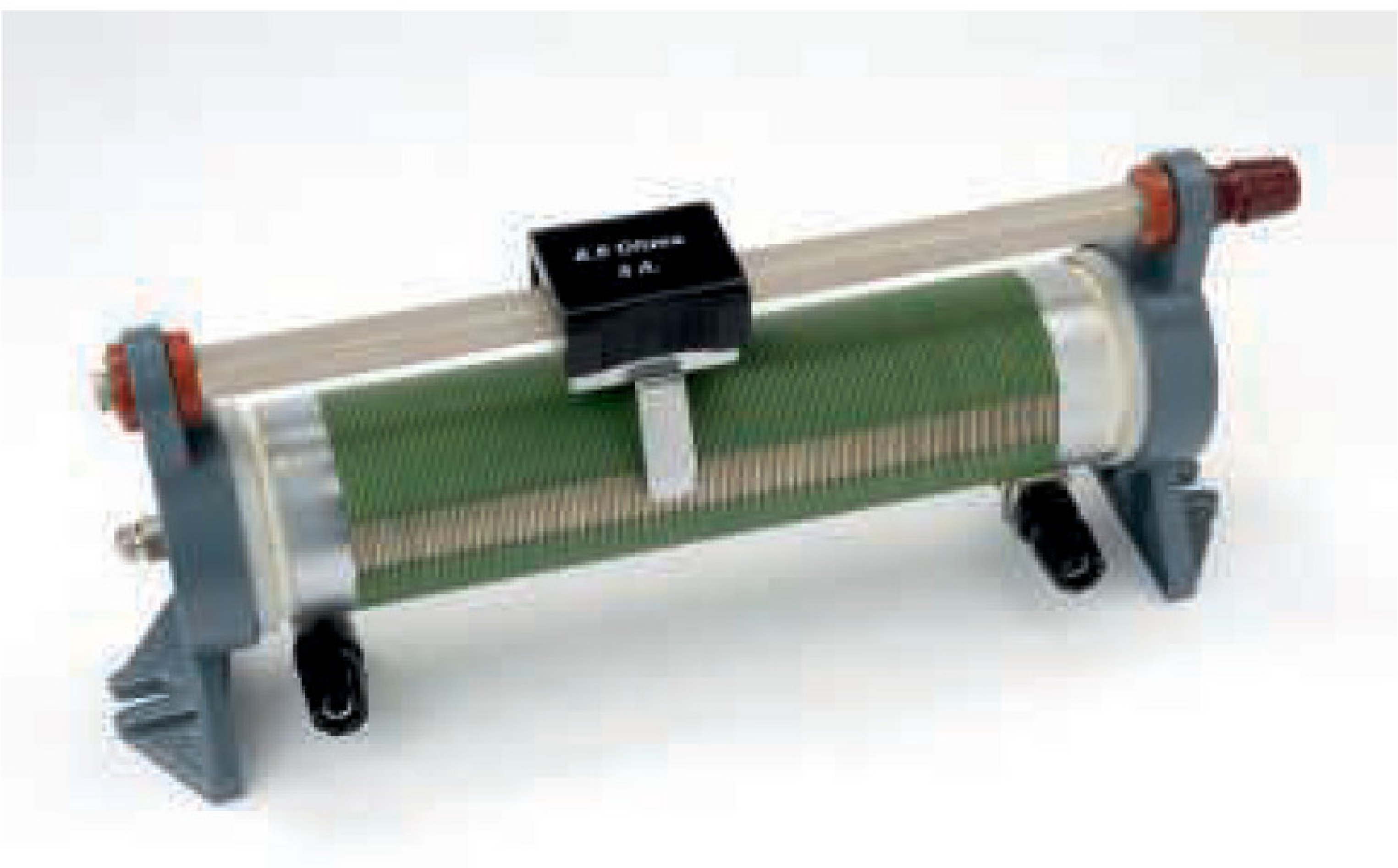


figure 7 A slide resistor for use in schools.

PLUS SPECIFIC RESISTIVITY

The resistance of a tungsten wire at a given temperature is not the same as that of an identical iron wire at the same temperature. It seems that the resistance depends on the type of material. That property of the substance is called the **resistivity** (symbol ρ, table 1). Insulators have a high resistivity. The specific resistivity of PVC, for example, is 10^{12} Ωm (you call this unit 'ohm-metres').

table 1 Resistivity at room temperature.

substance	resistivity ρ (× 10^{-6} Ωm) at 20 °C
aluminium	0.027
constantan	0.45
gold	0.022
iron	0.105
copper	0.017
steel	0.18
tungsten	0.055
silver	0.016

In addition to the temperature, a wire's resistance also depends on the length, the cross-section and the material it is made of. You can calculate the resistance of a wire using the following formula:

$$R = \frac{\rho \cdot l}{A}$$

where:

- R is the resistance in ohms (Ω);
- ρ is the resistivity in ohm-metres (Ωm);
- l is the length in metres (m);
- A is the surface area of the wire cross-section in square metres (m^2).

EXAMPLE EXERCISE 2

Copper wire is used for electricity cables in the home.
Calculate the resistance of 10 m of copper wire with a diameter d of 1.6 mm.

given $\rho = 0.017 \cdot 10^{-6}$ Ω m (table 1)
$l = 10$ m
$d = 1.6$ mm $= 1.6 \cdot 10^{-3}$ m

required $R = ?$

working $r = 0.5 \times d = 0.5 \times 1.6 \cdot 10^{-3} = 0.80 \cdot 10^{-3}$ m

$$A = \pi \cdot r^2 = \pi \cdot (0.80 \cdot 10^{-3})^2 = 2.01 \cdot 10^{-6}\ \text{m}^2$$

$$R = \frac{\rho \cdot l}{A} = \frac{0.017 \cdot 10^{-6} \times 10}{2.01 \cdot 10^{-6}} = 0.085\ \Omega$$

Note: don't round interim results off when calculating the value of A.

Practice the concepts using the *Flash cards*.

COURSE MATERIAL

1

Answer the following questions.

a What formula can you use to calculate the resistance of an electrical component?
b What is special about an ohmic resistance?
c What is the special property of wires that are made of constantan?
d Why does Ohm's law not apply to the wire (filament) in an incandescent bulb?
e What electrical component has a lower resistance as its temperature rises?

2

Complete the missing data in table 2.

table 2 Various variables and their units.

variable	symbol	unit	symbol
voltage			
	I		
		ohm	

IN PRACTICE

3

A mixer, a light and a kettle are connected to the mains (230 V).

- A current of 1.4 A goes through the mixer.
- A current of 48 mA goes through the bulb.
- A current of 9.6 A goes through the kettle.

Calculate the resistance of each device.

4

In an experiment, Peter lights an incandescent bulb using a battery (4.5 V). He uses a setup with an ammeter and a computer to measure the current. After the experiment has ended, he gets the computer to draw a graph of the first 25 ms after switching on the power (figure 8).

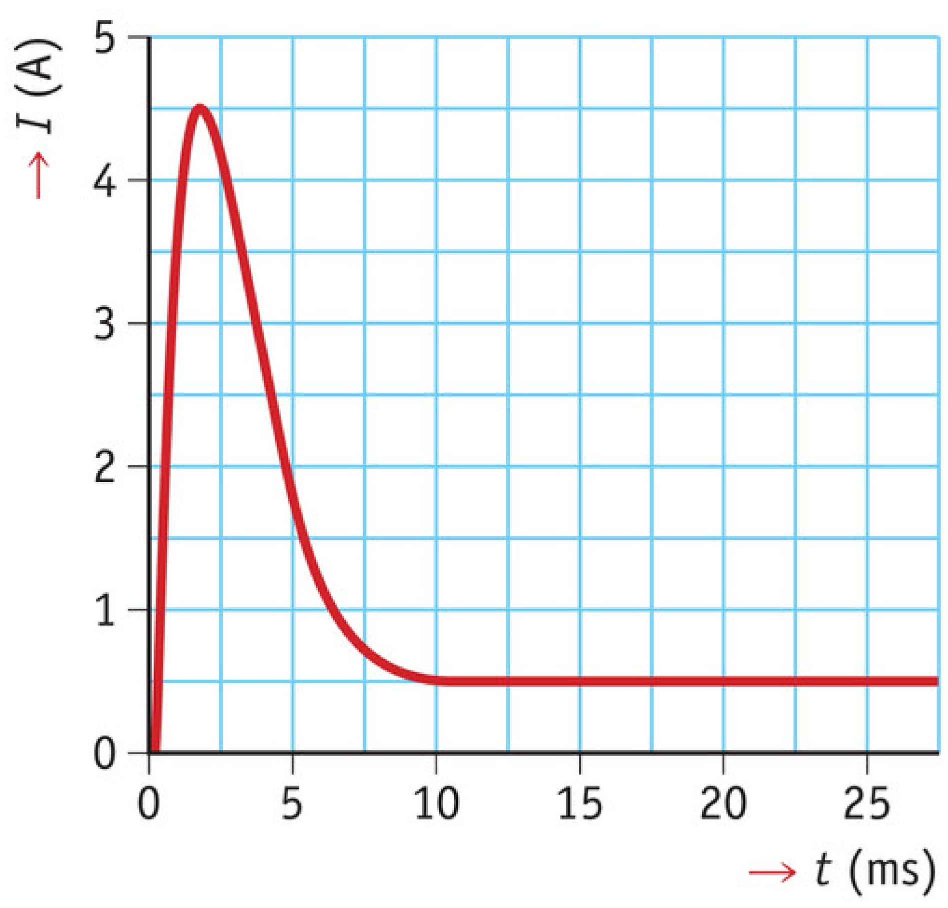


figure 8 The graph of Peter's experiment.

a How can you tell that the resistance of the filament was not constant?
b Calculate the resistance of the filament at the maximum current.
c Why does the current decrease strongly after that?
d After a while, the current reaches a constant value.
Calculate the resistance of the filament then.

5 Mo has connected a constantan wire of 6.0 Ω to a power supply box. He measures a current of 0.25 A.

a Calculate what voltage Mo has set the power supply box to.
b Mo turns the adjuster knob of the power supply box until the ammeter shows 0.75 A. Calculate what the voltage is now.
c Check your answer to Exercise (b) with a calculation.

6 Asha lets an incandescent bulb light up at different voltages. She measures the current each time. These measurements are given in table 3.

a Draw the associated (I,U) diagram in figure 9.

table 3 Asha's measurements.

spanning (V)	stroomsterkte (A)
2.0	0.18
4.0	0.26
6.0	0.32
8.0	0.37
10.0	0.41
12.0	0.44



figure 9 The graph with Asha's measurements.

b The resistance in the bulb changes as the bulb starts to light up more brightly. How can you tell this from the graph?
c Using the information in the graph, explain whether the resistance increases or decreases when the bulb starts to light up more brightly.
d Determine the resistance of the bulb at a voltage of 7.0 V.
e Using the information in the graph, explain whether Ohm's law works for this bulb.

7 Rick is building a simple lightmeter in a practical (figure 10). The battery of the meter delivers a voltage of 3.0 V.

a When Rick holds the LDR in bright sunlight, the current is 0.22 A. Calculate the resistance of the LDR.
b The current is only 0.10 mA six hours later. Calculate the resistance of the LDR.
c How can the resistance of the LDR have become so much higher in six hours?

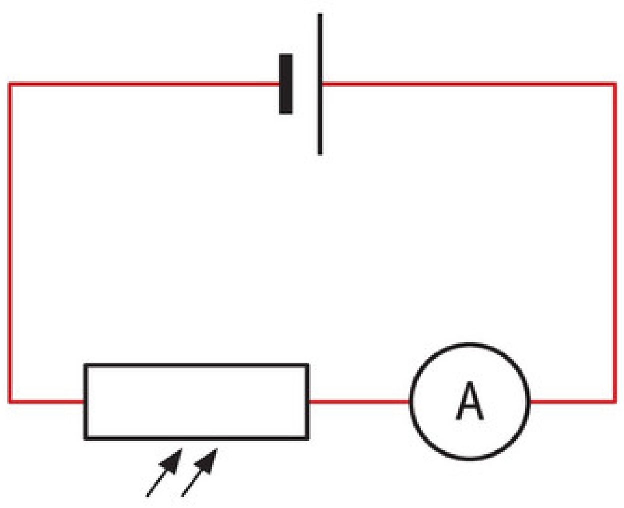


figure 10 The circuit diagram for Rick's lightmeter.

8 Joanne is doing the experiment that has been drawn in figure 11. She reads off the temperature of the water from the thermometer. She is using a multimeter to measure the resistance of the NTC thermistor. You can see her measurements in table 4.

a Draw the graph of Joanne's measurements in figure 12.

b Use this graph to read off how high the temperature is:

- when the multimeter shows 600 Ω;
- when the multimeter shows 150 Ω;
- when the multimeter shows 80 Ω.

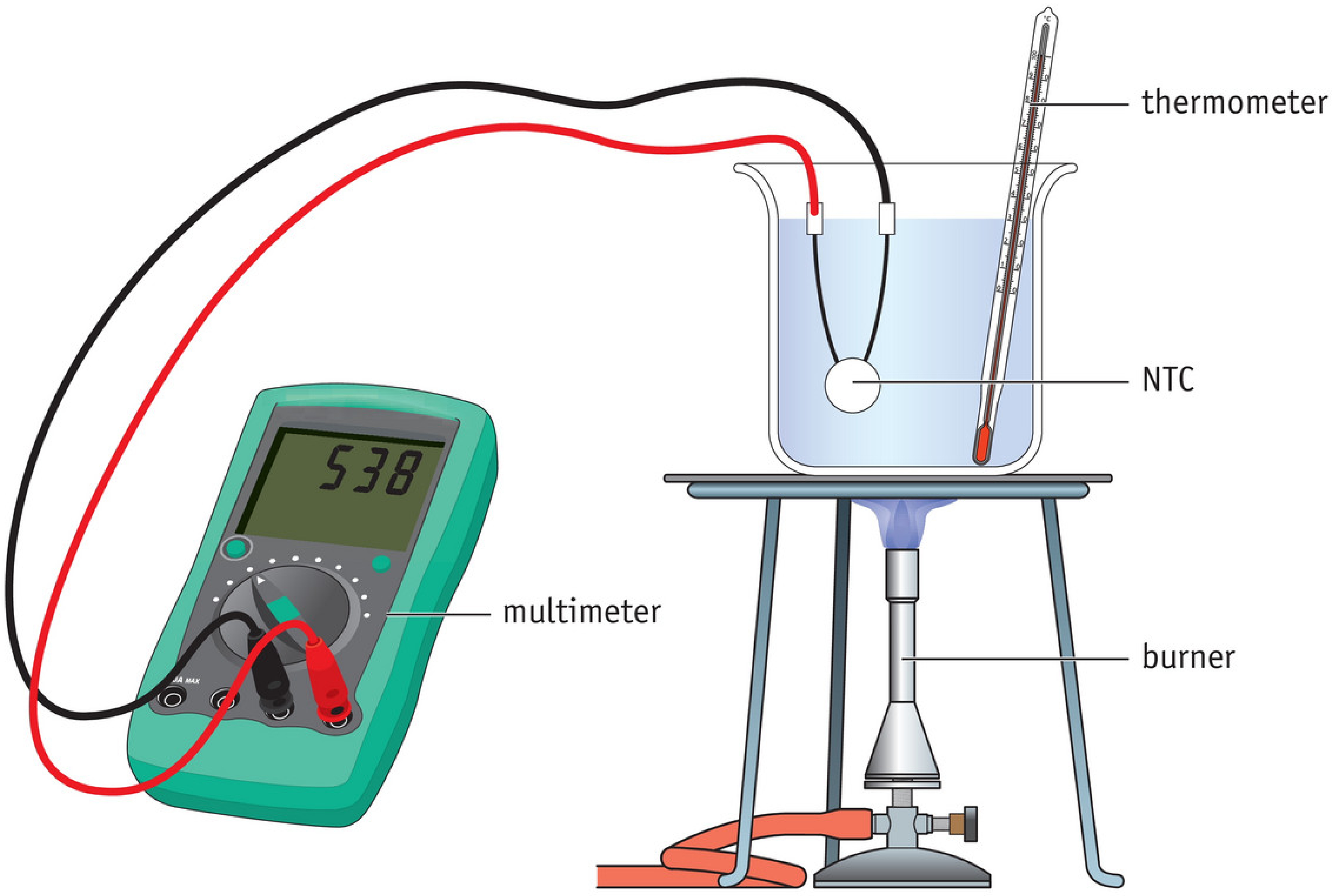


figure 11 Joanne's experimental setup.

table 4 Joanne's measurements.

temperature (°C)	resistance (Ω)
20	1249
30	785
40	511
50	341
60	255
70	176
80	129
90	96
100	72

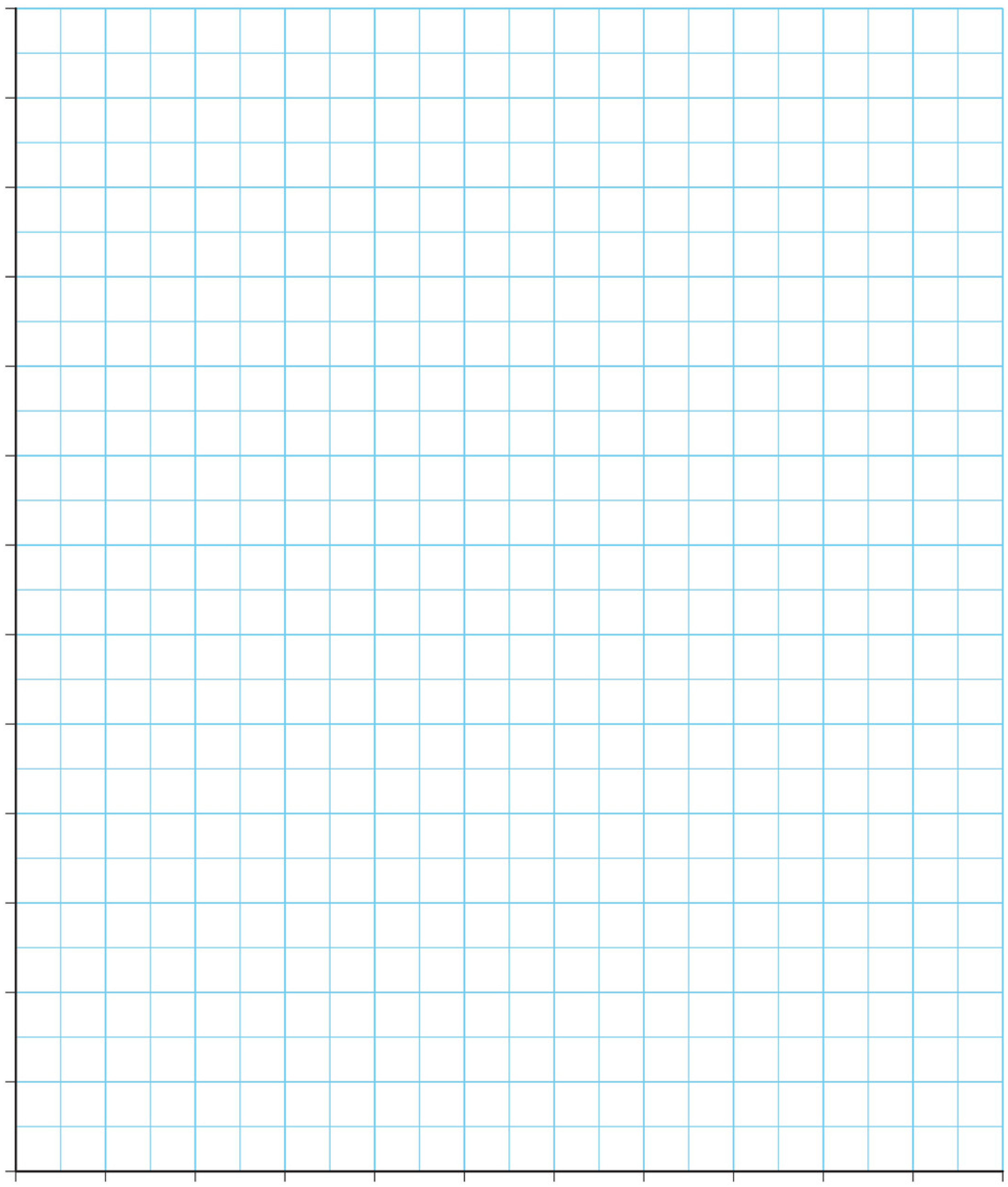


figure 12 The graph with Joanne's measurements.

★ 9 Chloe needs a resistor of 28 Ω. She finds a website that tells her how she can make such a resistor (figure 13).

a How many metres of wire does Chloe need to measure off:
- if she uses resistance wire of 2.5 Ω/m?
- if she uses resistance wire of 63 Ω/m?

b Chloe wants to wrap the wire for her resistor around a ballpoint pen.
Explain which kind of wire she is best off using: the wire of 2.5 Ω/m, or the wire of 63 Ω/m?

c Ben made a 112 Ω resistor by wrapping 4.0 metres of resistance wire around a deodorant bottle.
Calculate the resistance per metre of the wire he used.

Resistance wire

If you need a resistor of a specific value, you can see whether you can buy it. But you can also make your own resistors. You can buy special resistance wire for this.
For example, resistance wire of 2.5 ohms per metre (Ω/m) is available in stores. That means one metre of this wire gives a resistance of 2.5 Ω. Two metres of this wire has a resistance of 2 × 2.5 = 5.0 Ω, three metres has a resistance of 3 × 2.5 = 7.5 Ω, and so forth.
To make a resistor with a certain value, you need to cut off the right length of wire. Then you wrap the wire around a rod in a spiral.

Resistance wire, 2.5 Ω/m



For making resistors with specific ratings in Ω

figure 13 Making your own resistors.

Test what you know with *Test yourself*.

PLUS SPECIFIC RESISTIVITY

10 Lily wants to determine the resistivity of iron. She decides to do that by using a voltmeter and an ammeter to determine the resistance of a piece of iron wire.

a Draw the circuit that Lily uses.

b She measures a current of 0.14 A for a voltage of 0.50 V.
Calculate the resistance of the wire.

c The wire is 100 cm long and has a diameter of 0.20 mm.
Calculate the specific resistivity of iron.

d Compare the answer to Exercise (c) against the number in table 1 and give an explanation for the difference.

★ 11 Ewan has a bobbin with copper wire. He wants to know how many metres of wire are still on the bobbin. He doesn't feel like unwinding the wire off the bobbin and measuring it. So he determines the length by measuring the resistance. The text on the bobbin says that the wire has a diameter of 0.25 mm.

a Calculate the cross-sectional area of the wire.

b Ewan measures a resistance of 1.2 Ω.
Calculate the length of the wire.

c Explain why Ewan needs to do his measurements immediately after connecting the voltage.

12 A pupil wants to determine the ratio between the resistance of two wires A and B. The wires are made of the same material.
Wire A is 1.0 m long and has a diameter of 0.2 mm; call the resistance for this wire R_A.
Wire B is 0.5 m long and has a diameter of 0.4 mm; call the resistance for this wire R_B.
Which of the following statements is correct?

- ○ A $R_A = 8 \cdot R_B$
- ○ B $R_A = 4 \cdot R_B$
- ○ C $R_A = 2 \cdot R_B$
- ○ D $R_A = R_B$

After: IJSO

3 Connecting resistors

LEARNING OBJECTIVES

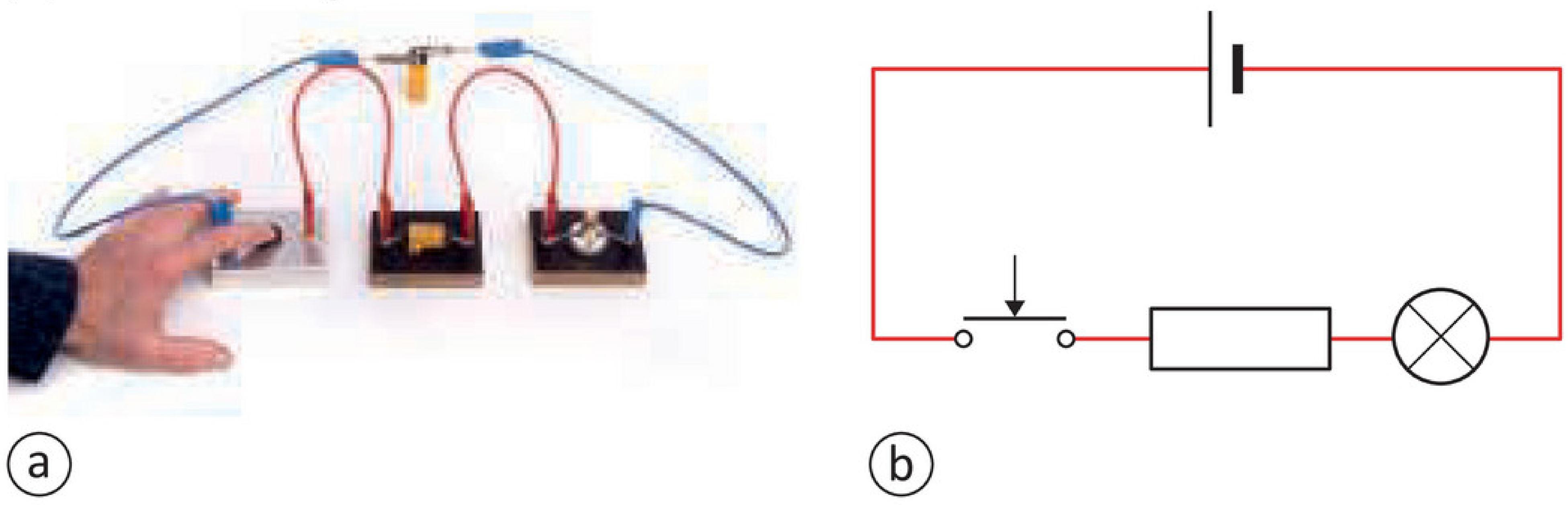
5.3.1 You can explain the difference between a resistor (the component) and resistance (the variable).
5.3.2 You can calculate the equivalent resistance to the resistors in a series circuit.
5.3.3 You can calculate the voltages U_1, U_2, U_3 and so forth across each resistor in a series circuit.
5.3.4 You can calculate the equivalent resistance to the resistors in a parallel circuit.
5.3.5 You can calculate the currents I_1, I_2, I_3 and so forth through each resistance in a parallel circuit.
PLUS 5.3.6 You can explain how PTCs and NTCs work in circuits and demonstrate this with calculations.

Mobile phones and laptops have complex circuits with hundreds of components. The designer of such a circuit always looks carefully at the current through these components and adds one or more resistors if necessary. The current could otherwise get too large and cause components to overheat and break.

WORKING WITH RESISTORS

If you connect a 6 V bulb to a 9 V voltage, the current gets too high and the bulb burns out. You can prevent that by increasing the overall resistance of the circuit. To do that, you place a resistor in series with the bulb (figure 1a). In a circuit diagram, you draw a component with a constant resistance as a rectangle (figure 1b).

figure 1 The resistor makes sure that the bulb does not burn out: (a) the setup and (b) the circuit diagram.



Please note the difference between 'resistor' and 'resistance': a 'resistor' is an object (a component in a circuit) and the 'resistance' is a variable (the number of ohms). You can see that in the following sentence: "This resistor has a resistance of 6 Ω."

RESISTORS IN SERIES

EXP. 3

If you connect more and more resistors in series, the resistance of the whole circuit will get higher and higher. The current will decrease more and more if the voltage stays the same. You can calculate the total resistance R_{tot} by adding all the individual resistances (figure 2):

$$R_{tot} = R_1 + R_2 + R_3 + \dots$$

where:
- R_{tot} is the total resistance in ohms (Ω);
- R_1, R_2, R_3 are the resistances of the first, second and third circuit components in ohms (Ω).

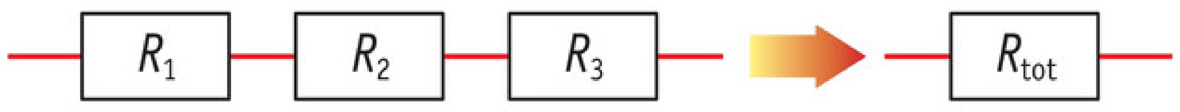


figure 2 Resistances connected in series are added up.

If you replace all the individual resistors with a single resistor with the value of R_{tot}, it will have no effect on the rest of the circuit. That is why the total resistance is called the **equivalent resistance**.

CURRENT AND VOLTAGE IN A SERIES CIRCUIT

The current I is equally high everywhere in a series circuit. There are no branches where the current has to split. However, the voltage in a series circuit is split across the various circuit components. If you connect two bulbs of the same type in series and connect them to a 9.0 V battery, each bulb will be lit at 4.5 V: each bulb gets half the source voltage.

If the two bulbs have different resistances, the source voltage U_{tot} will not be divided exactly in two. Bulb 1 has then a voltage of $U_1 = I \cdot R_1$ and bulb 2 has a voltage of $U_2 = I \cdot R_2$. When you add them up, U_1 and U_2 equal the source voltage.

$$U_{tot} = U_1 + U_2 + \dots$$

where:
- U_{tot} is the voltage across the entire circuit in volts (V);
- U_1, U_2 are the voltages across the first and second circuit components in volts (V).

Resistors are often used to make sure that other components work at the correct voltage. Figure 3 gives an example. Because the voltage of the battery is too high for the LED bulb, it is connected in series with a resistor. Only part of the voltage is then across the resistor. The rest of the voltage is exactly high enough to make sure the LED bulb will be lit properly.

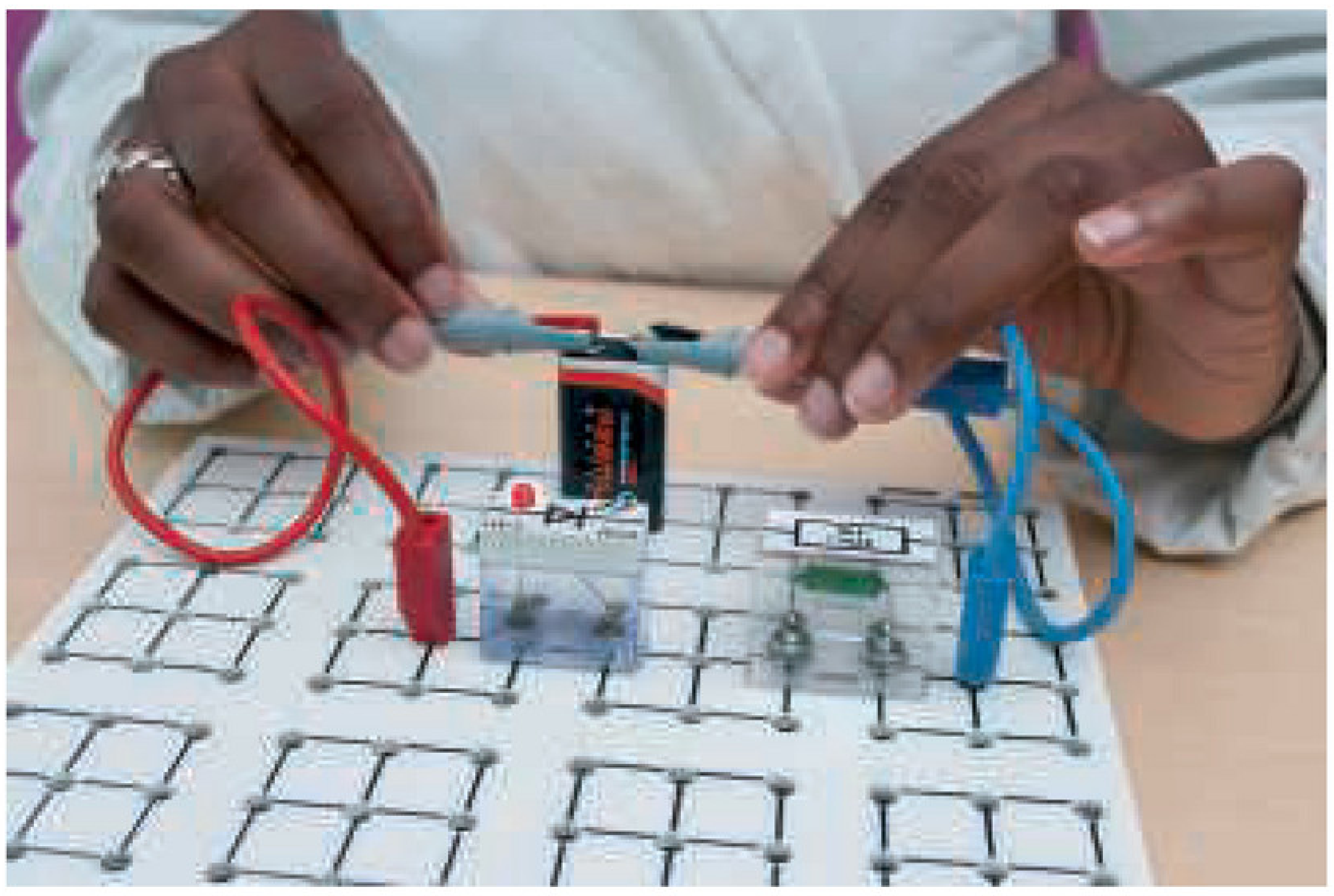


figure 3 A LED bulb is connected in series with a ballast resistor.

EXAMPLE EXERCISE 1

The LED bulb in figure 3 is lit just right when the voltage is 2.0 V. A current of 20 mA then flows through the bulb. The battery delivers a voltage of 9.0 V.
Calculate what the value of the resistor R_2 must be to make sure the bulb is lit at the right voltage.

given $U_1 = 2.0$ V
$U_{tot} = 9.0$ V
$I = 20$ mA $= 0.02$ A

required $R_2 = ?$

working $U_{tot} = U_1 + U_2$
$9.0 = 2.0 + U_2$
$U_2 = 7.0$ V

$$R_2 = \frac{U_2}{I} = \frac{7.0}{0.020} = 3.5 \cdot 10^2\ \Omega$$

RESISTORS IN PARALLEL

EXP. 4

If you connect more and more resistors in parallel, the total resistance of the circuit will not be higher – as in a series circuit – but lower. Because the number of branches increases, the current can flow more easily. If the voltage stays the same, the current will therefore keep increasing.

That is why you cannot just keep connecting more and more appliances in parallel: the wires supplying the circuit could soon get overloaded. To prevent overloads, a domestic electricity supply is divided up into groups: each group can take a limited number of appliances. This method is used not only for the domestic electricity supply but also for the lighting rig at a big concert (figure 4).



figure 4 A lighting rig is divided into groups, just like a domestic electricity system.

You can calculate the total resistance R_{tot} of a parallel circuit (figure 5) using the formula:

$$\frac{1}{R_{tot}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$$

where:

- R_{tot} is the total resistance in ohms (Ω);
- R_1, R_2, R_3 are the resistances of the first, second and third components in ohms (Ω).

This formula shows that the total resistance (or the equivalent resistance) is always lower than any of the individual resistors R_1, R_2 and so forth.

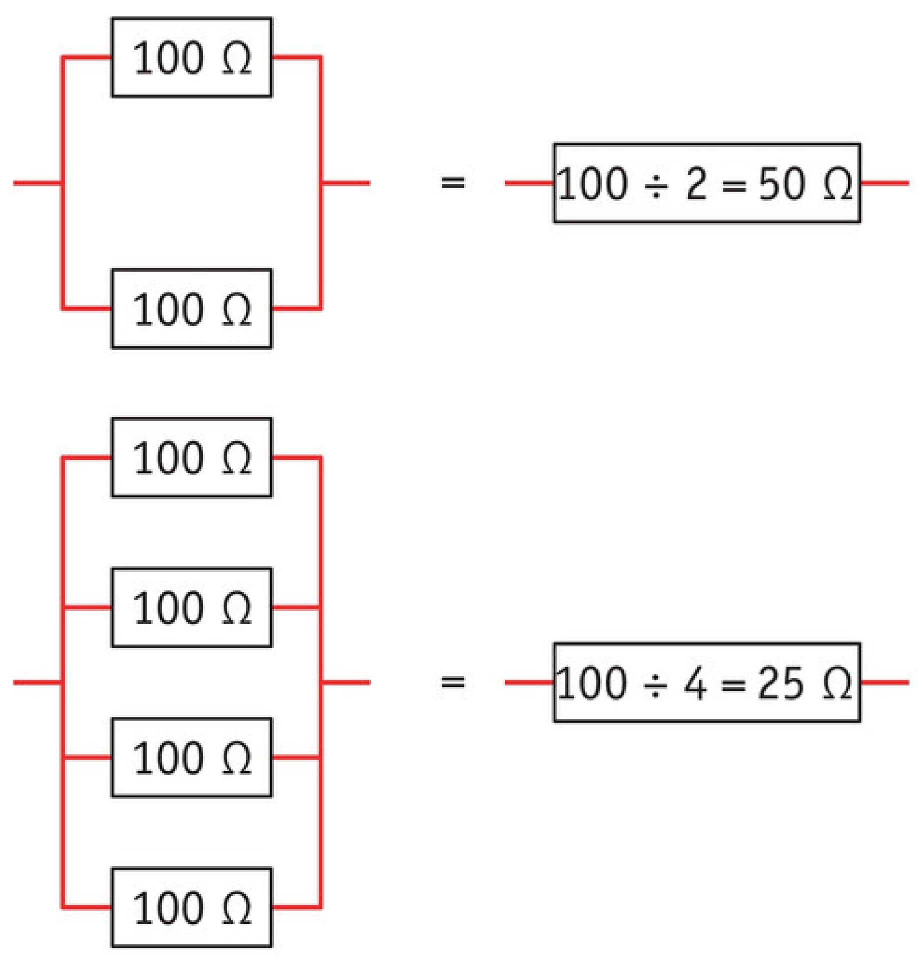


figure 5 The equivalent resistance becomes smaller as you place more resistors in parallel.

EXAMPLE EXERCISE 2

Esther connects a 55 Ω resistor in parallel with a 145 Ω resistor.
Calculate the equivalent resistance.

given $R_1 = 55\ \Omega$
$R_2 = 145\ \Omega$

required $R_{tot} = ?$

working $\frac{1}{R_{tot}} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{55} + \frac{1}{145} = 0.025$

$R_{tot} = \frac{1}{0.025} = 40\ \Omega$

CURRENT AND VOLTAGE IN A PARALLEL CIRCUIT

Each component in a parallel circuit is connected directly to the voltage source. This means that the full source voltage U_{tot} is present across each component. The rule for the voltage is:

$$U_{tot} = U_1 = U_2 = U_3 \ldots$$

In a parallel circuit, the current is split between the various branches (figure 6). The **total current** is the current in the part that is not split into branches: the power supply wires that all the current has to flow through. You can therefore calculate the total current using the formula:

$$I_{tot} = I_1 + I_2 + I_3 + \ldots$$

where:

- I_{tot} is the total current in the unbranched part in amps (A);
- I_1, I_2 and I_3 are the currents through the first, second and third branches in amps (A).

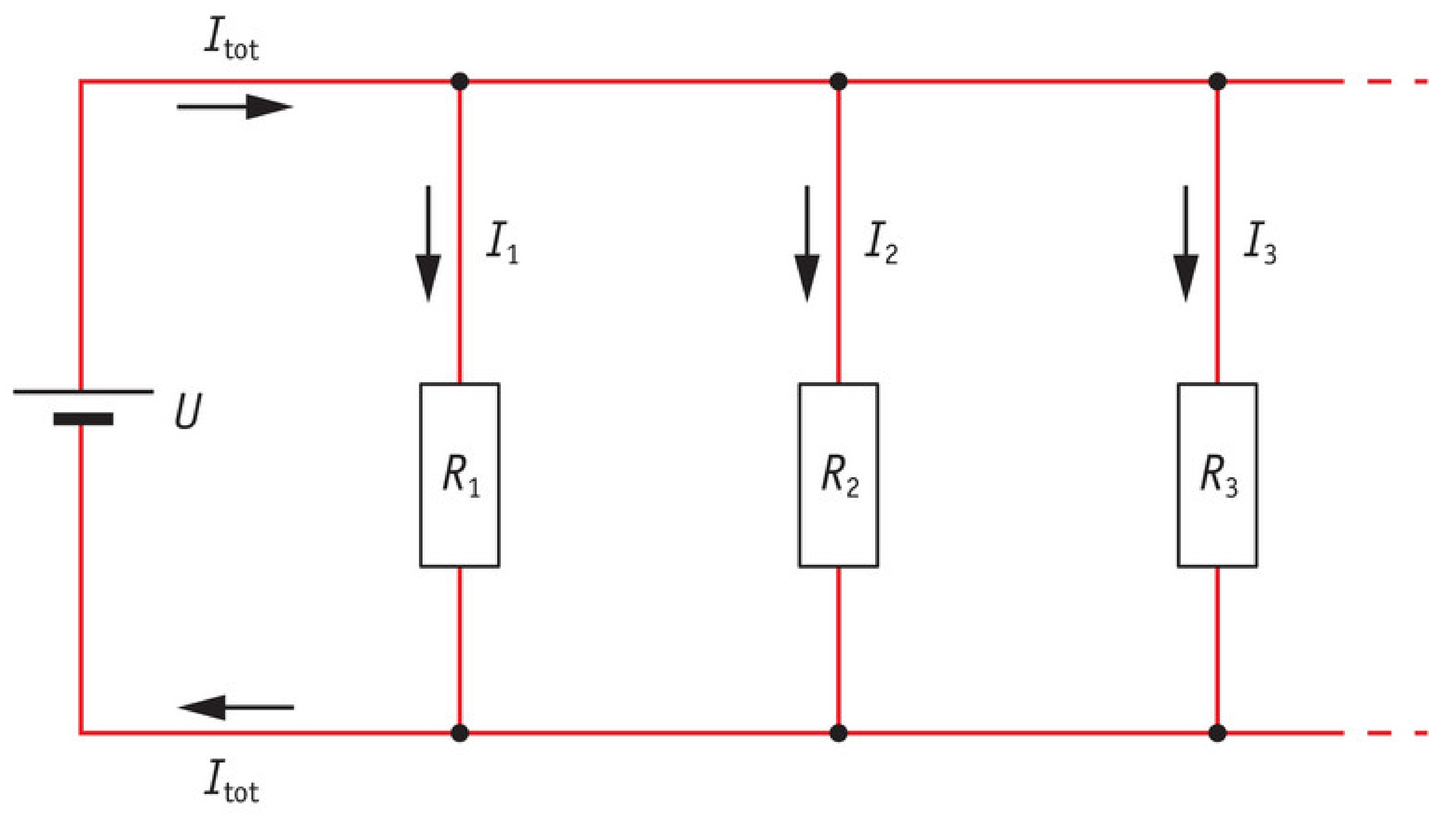


figure 6 The current splits in a parallel circuit.

There is a risk of overload in the part that is not split into branches if too many circuit components are connected at the same time.

EXAMPLE EXERCISE 3

Calculate the total current in the circuit from Example Exercise 2 if you connect the resistors to a voltage source of 9.0 V.

given $R_1 = 55\ \Omega$
$R_2 = 145\ \Omega$
$U = 9.0$ V

required $I_{tot} = \ldots$

working $I_1 = \dfrac{U}{R_1} = \dfrac{9.0}{55} = 0.164$ A

$I_2 = \dfrac{U}{R_2} = \dfrac{9.0}{145} = 0.0621$ A

$I_{tot} = I_1 + I_2 = 0.164 + 0.0621$

$I_{tot} = 0.23$ A

You get the same result if you divide the source voltage by the total resistance:

$$I_{tot} = \frac{U}{R_{tot}} = \frac{9.0}{40} = 0.23 \text{ A}$$

PLUS THE PTC AND NTC IN CIRCUITS

A PTC works in the opposite way to an NTC. As the temperature of a PTC increases, its resistance increases too. PTCs and NTCs are sensitive to changes in temperature. That is why they are used a lot in circuits. Many appliances work best at normal ambient temperatures. If the temperature of the LCD display on a smartphone gets too low, for example, the contrast is less. If an NTC is included in the circuit, the voltage across the chip that controls the screen increases and that makes the contrast go back up again.

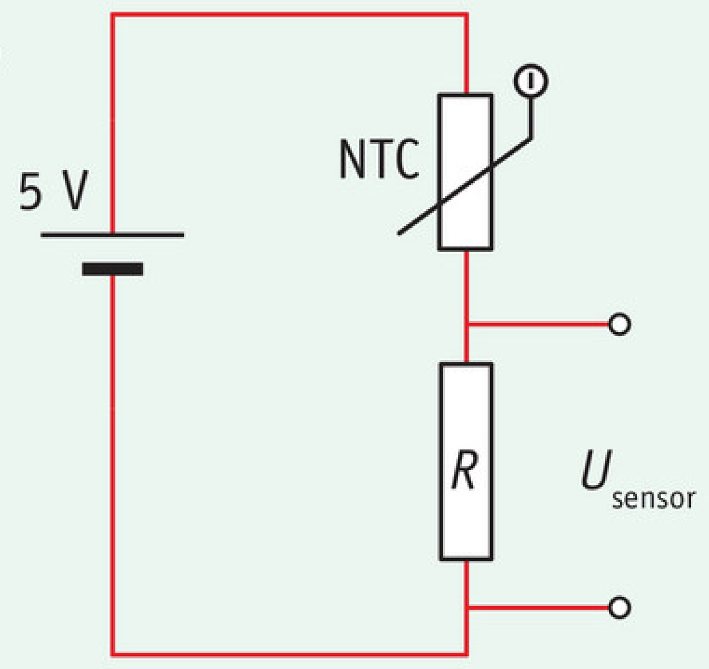


figure 7 A temperature sensor with an NTC.

Resistors like these are also used in temperature sensors: circuits delivering a voltage that depends on the temperature. For example, a light comes on in a deep fat fryer when the oil has reached the right temperature. Temperature sensors also let the central heating come on automatically if it gets too cold, and cooling elements switch on in a freezer if it gets too warm.

Figure 7 gives an example of a temperature sensor using an NTC and a fixed resistor *R*. As the temperature increases, the voltage across the fixed resistor increases. You can then pass this voltage on to another circuit to switch on a warning light, for example.

PTCs are often used to protect components against currents that are too high. If a component starts to get too hot because the current is too high, the PTC's resistance increases and that limits the increase in the current.

Practice the concepts using the *Flash cards*.

COURSE MATERIAL

1 Answer the following questions.

a How can you connect a bulb safely to a battery of 9 V if the bulb has been designed for a voltage of 6 V?

b How does the total resistance of a series circuit change if you keep on increasing the number of resistors?

c Why is the total resistance of a number of resistors also called the 'equivalent resistance'?

d What formula can you use to calculate the equivalent resistance to three resistors that are connected in parallel?

2

Underline the correct circuit type.

a The current in a *parallel* / *series* circuit is the same everywhere.

b The current in a *parallel* / *series* circuit splits at every branch.

c The full voltage is present across each circuit component in a *parallel* / *series* circuit.

d The voltage in a *parallel* / *series* circuit is split across the various circuit components.

IN PRACTICE

3

Study the series circuit drawn in figure 8.

a Calculate the total resistance.

b Calculate the current.

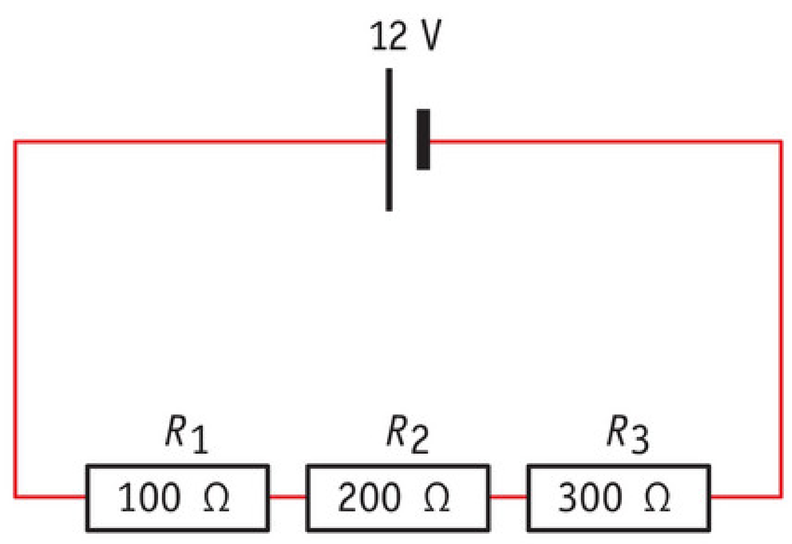


figure 8 A series circuit.

★ 4

A wireless microphone works on a battery of 9.0 V. When you switch on the voltage, a LED lights up (figure 9). A ballast resistor R_1 is used to let the LED light up at its correct voltage of 2.0 V. The current flowing through the LED is then 18 mA.
Calculate the value of the resistor R_1.

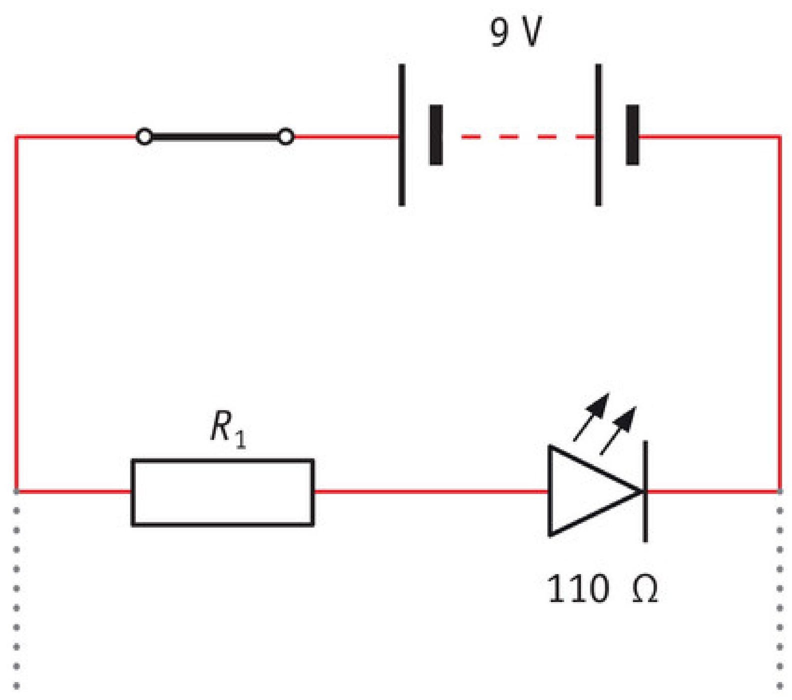


figure 9 A LED with a ballast resistor.

5

A moped battery delivers 6.0 V. The headlight (R_1 = 20 Ω) and rear light (R_2 = 120 Ω) are connected in parallel.

a Calculate the equivalent resistance.

b Calculate the total current.

★ 6

The circuit in figure 10 has three identical bulbs. If only switch 1 is closed, bulb A will be lit at the normal voltage.
Are there any other bulbs that are lit at the normal voltage when switch 2 is closed too? Explain your answer.

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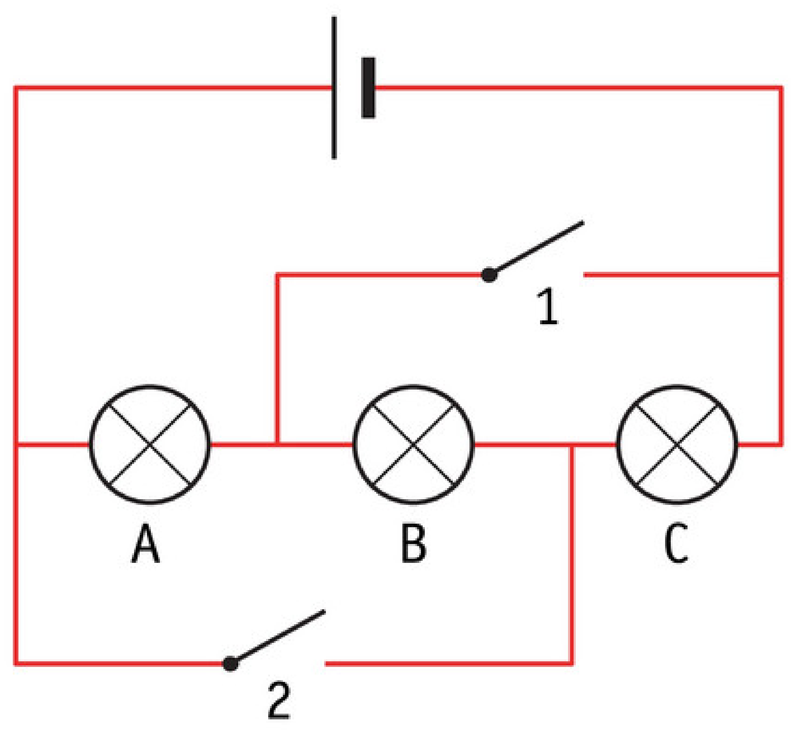


figure 10 A circuit with three bulbs.

7

The hob of an electric stove has two heating elements, R_1 and R_2. R_1 has a resistance of 65 Ω, R_2 has a resistance of 35 Ω. The hob is connected to the mains (230 V).
Calculate the total current through the hob:

a if only R_1 is switched on.
b if only R_2 is switched on.
c if both R_1 and R_2 are switched on and connected in series.
d if both R_1 and R_2 are switched on and connected in parallel.

★ 8

Work out why (saying it without using numbers) the equivalent resistance in resistors connected in parallel is always less than the smallest resistance used.

9

Two resistors of 60 Ω and 40 Ω and a third unknown resistor R_3 are connected in parallel. The total resistance of the circuit is 15 Ω.
Calculate the value of resistor R_3.

★ 10

Alisha has four identical resistors of 20 Ω. She uses them to make a combination as shown in figure 11 and connects them to a voltage of 6.0 V.

a Calculate the total current.
b Calculate the highest and lowest overall resistances that you can make with these four resistors.

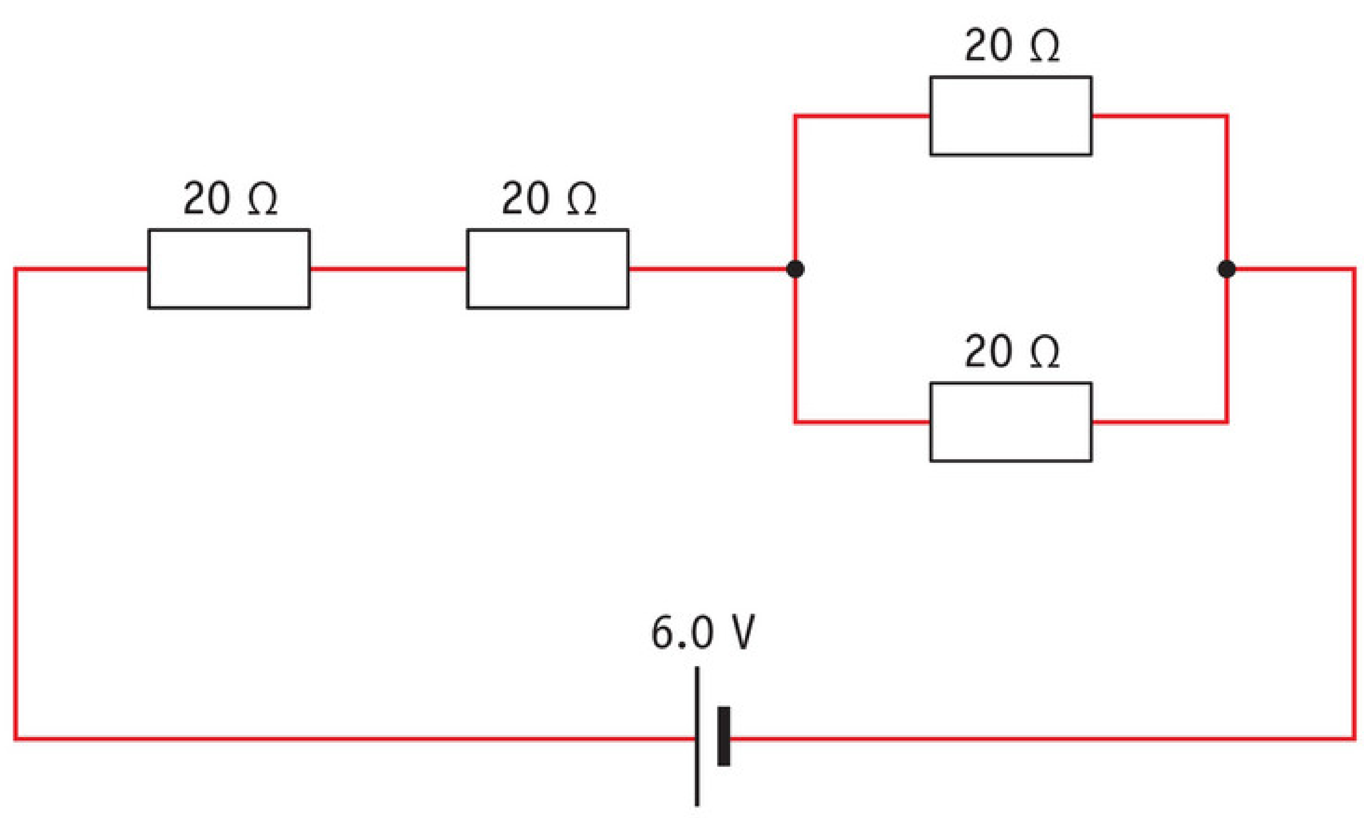


figure 11 Alisha's resistor combination.

Test what you know with *Test yourself.*

PLUS THE PTC AND NTC IN CIRCUITS

11 An electric motor in a fan can soon break if you block the fan by accident. That can cause too much current to flow through the motor. Figure 12 shows how you can use a PTC to protect the motor.

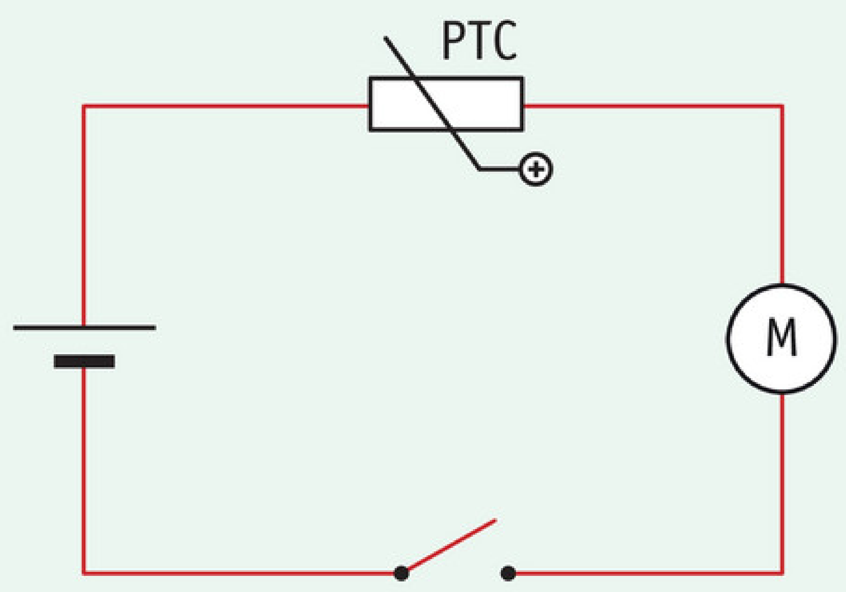


figure 12 A PTC protecting an electric motor.

a Explain how the PTC protects the motor when there is a surge (sudden increase) in the current in the circuit because the motor is blocked.

b Natalie switches on the blocked fan. This makes a large current flow through the circuit in figure 12.
Let's suppose that the blocked electric motor has a constant resistance. Explain what happens to the voltage across the PTC and the motor when this high current flows through the circuit.

12 Lisa reads information on the Internet about the use of NTCs in smartphones.

> The contrast in the LCD screens that are used in smartphones changes as the ambient temperature rises or falls. That is why the voltage across the chip that controls the light intensity has to be adapted as the ambient temperature changes. The greater the voltage across this chip, the greater the contrast.
>
> *After: https://product.tdk.com*

Figure 13 shows a simplified diagram of a circuit that does this. It includes an NTC and fixed resistors R.

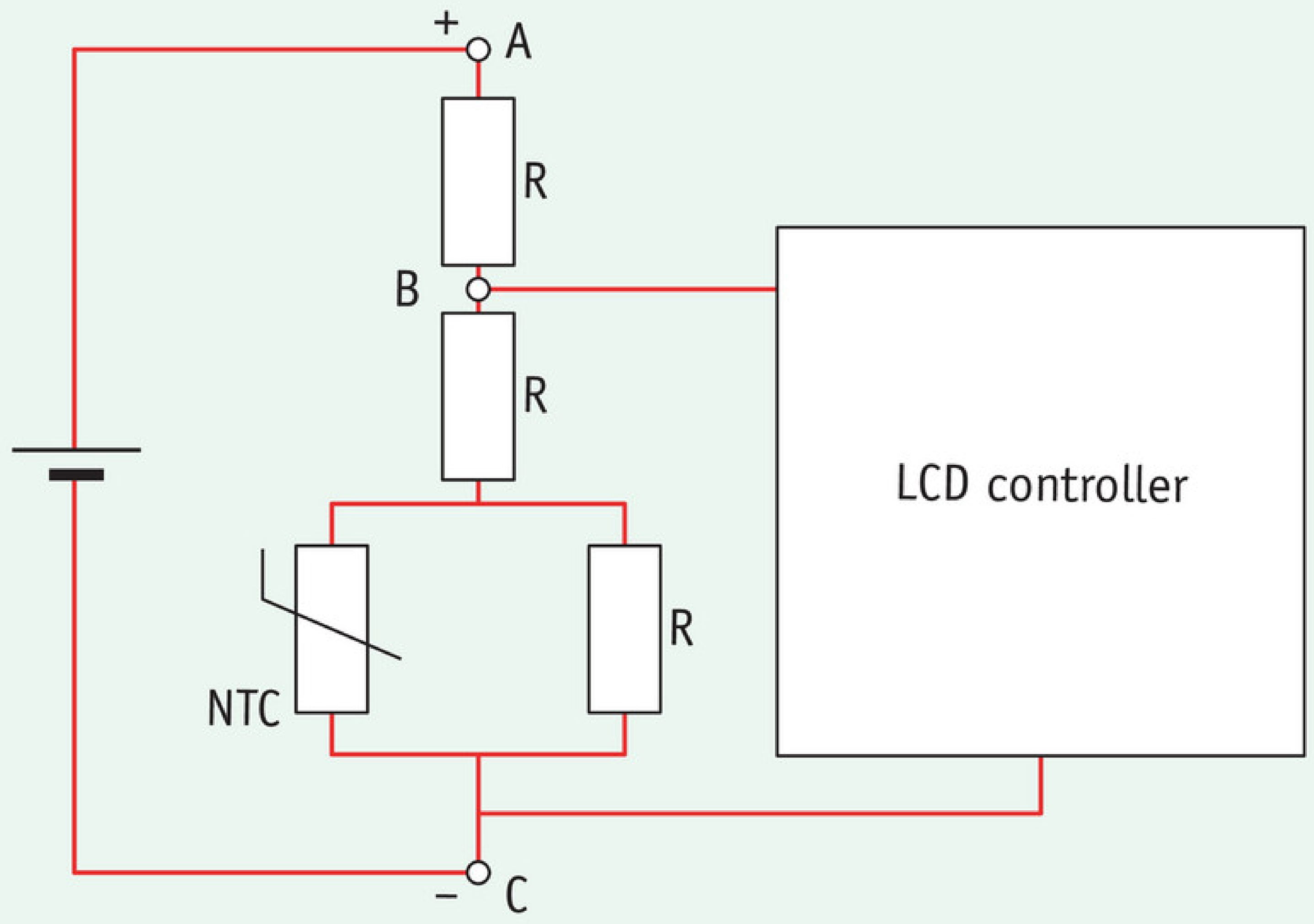


figure 13 The circuit controlling the voltage for the LCD controller.

a Explain what happens to the voltage between points A and B when the ambient temperature falls.

b Explain what happens to the voltage across the LCD controller if the ambient temperature falls.

c If the ambient temperature is low, the contrast in an LCD display becomes poorer. Explain how the circuit resolves that problem.

13 Figure 14 shows a circuit for measuring the temperature of the oil in a deep fat fryer. The graph in figure 15 shows how the resistance of the NTC depends on the temperature.

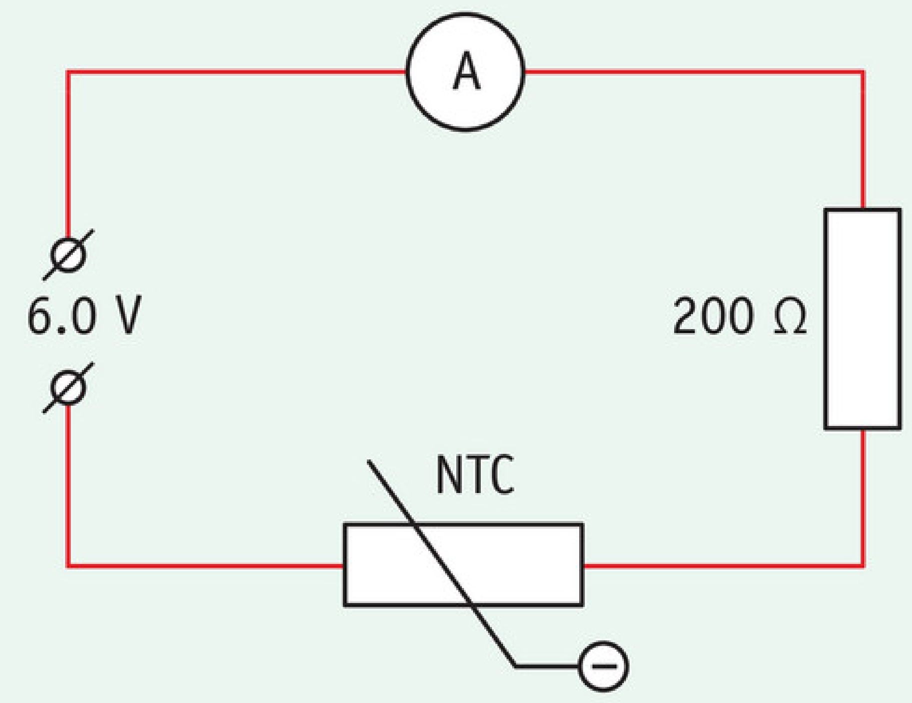


figure 14 This circuit lets you measure the temperature in a deep fat fryer.

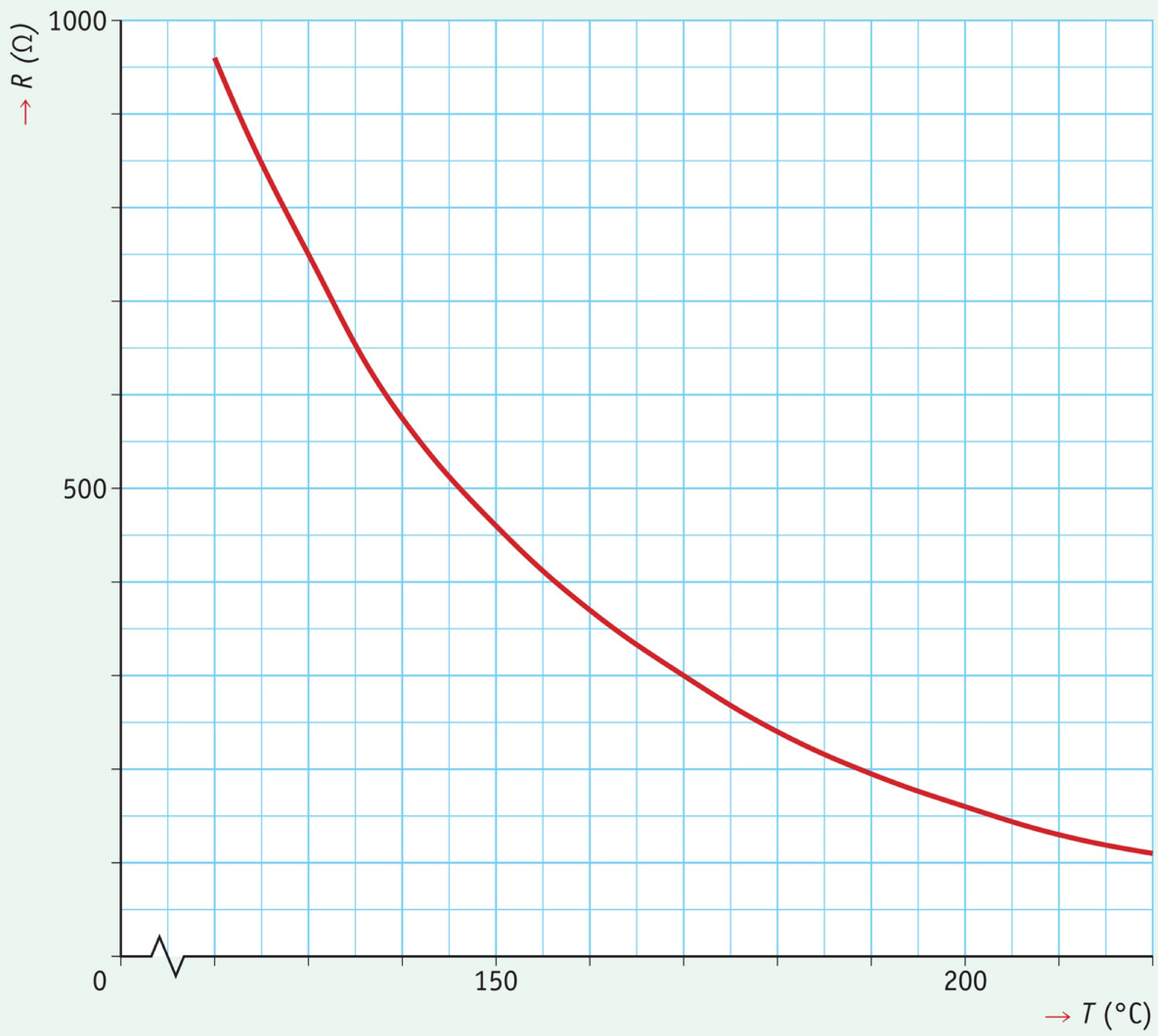


figure 15 How the value of the resistance of an NTC changes with temperature.

a Calculate the current in the circuit when the temperature is 190 °C and 170 °C.

b Figure 16 is a drawing of the graduated scale for the ammeter that was used. Write a division into degrees Celsius above the graduated scale. If you write down the two temperatures in the exercise, that is enough.

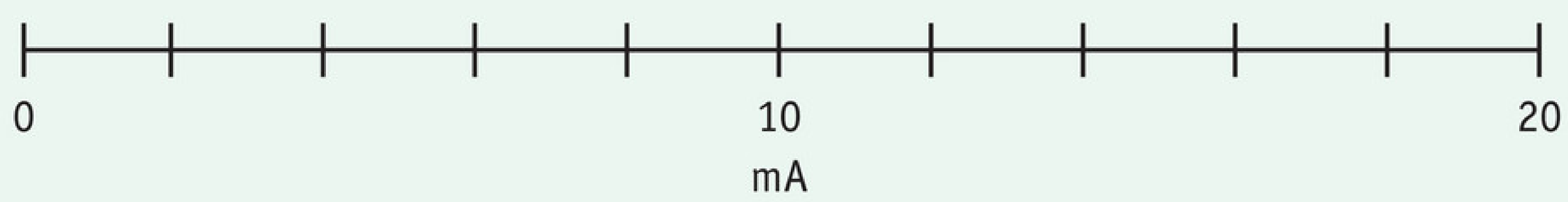


figure 16 A graduated scale.

c Wendy also wants to make a graduated scale but she wants to use a voltmeter instead of an ammeter. She wants to make sure that a higher temperature corresponds to a higher deflection of the voltmeter. She is not sure whether she should connect the voltmeter across the fixed resistor (200 Ω) or across the NTC.

Choose the correct options.
When the temperature increases, the resistance of the NTC *increases* / *decreases*.
As a result, the total resistance in the circuit *increases* / *decreases*.
Consequently, the current in the circuit *increases* / *decreases*.
That means that the voltage across the fixed resistor (200 Ω) *increases* / *decreases* and the voltage across the NTC *increases* / *decreases*.
Wendy should therefore connect the voltmeter across the *NTC* / *fixed resistor*.

4 Automatic circuits

LEARNING OBJECTIVES

5.4.1 You can explain what the functions are of the sensor, the switch and the actuator in an automatic circuit.
5.4.2 You can describe how a transistor works when it is used as a switch.
5.4.3 You can draw a circuit diagram for a simple circuit with a transistor, such as a burglar alarm or an automatic streetlight.
5.4.4 You can explain how the circuits for a burglar alarm and an automatic streetlight work.
PLUS 5.4.5 You can explain how the diode works in a rectifier.

A lot of cars have burglar alarms. If a car thief tries to force the doors, an alarm will sound and indicator lights will start flashing. The alarm may also activate an immobiliser system and block the fuel supply. This is all possible because of the circuits that detect the hazard and respond to it.

SENSOR – SWITCH – ACTUATOR

A lot of people have an outdoor light that turns on and off by itself. Such a light is operated by an automatic circuit that is made up of three parts: a sensor, a switch and an actuator.

Each component of the circuit has a function.

- The **sensor** produces an electrical signal that gives information about the surroundings. This lets it 'tell' the switch if anything has changed in the surroundings.
- The **switch** responds to the information from the sensor. If the signal from the sensor requires a response, it switches the power on or off.
- The **actuator** does something that is wanted at that moment: a light comes on, a siren starts sounding, a motor is started, or whatever (figure 1).



figure 1 The circuit in a smoke detector responds to even a small amount of smoke.

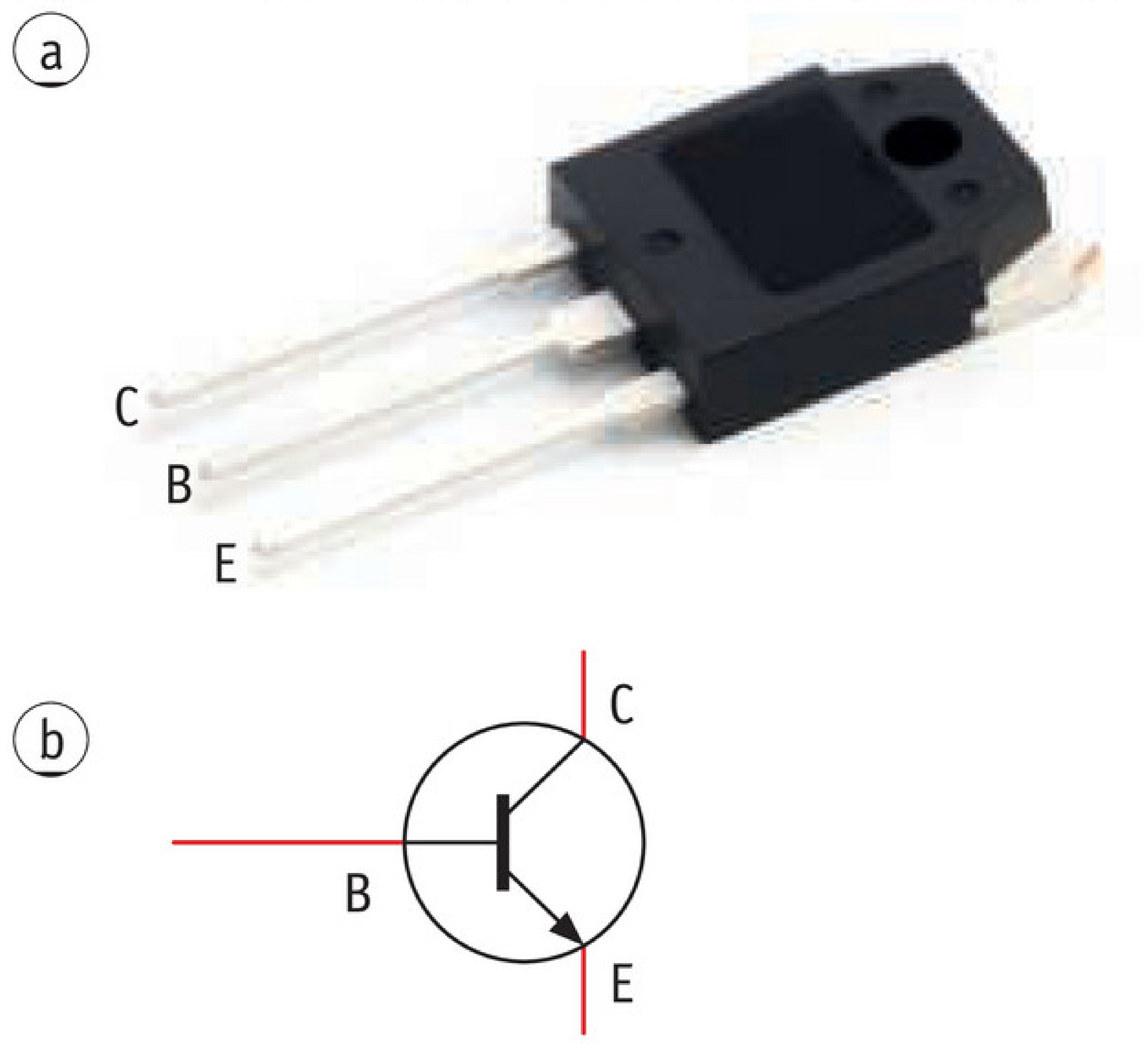
Some outdoor lights have a sensor that responds to the amount of daylight. When it gets dark, the signal from the sensor changes. A switch in the lamp then turns the bulb on. There are also outdoor lights that switch on when someone walks past. These lamps use an infrared detector as a sensor. This sensor responds to the infrared radiation given off by people and animals.

HOW A TRANSISTOR WORKS

In many automatic circuits, the actuators are switched on and off by a **transistor**. In that case, such a transistor acts as an automatic switch. As you can see in figure 2, a transistor has three terminals:

- the **collector** (C)
- the **base** (B)
- the **emitter** (E)

figure 2 A transistor and the corresponding circuit symbol.

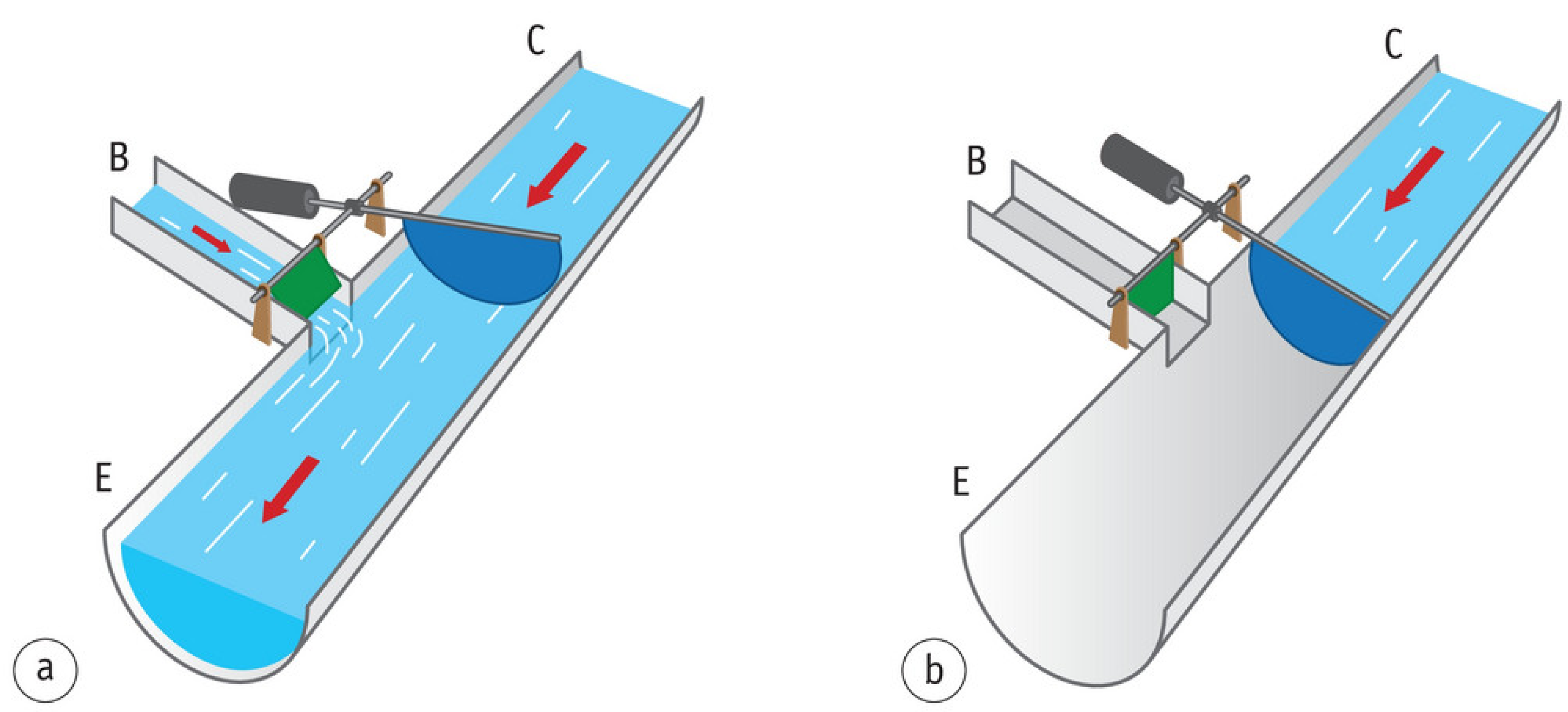


You can compare the way that a transistor works to the way a traffic barrier works. A barrier is raised or lowered to allow the traffic on a road to pass or stop: a transistor does the same with the current to a device.

In the ON position, the transistor allows the current to pass, but in the OFF position it blocks the current.

- The transistor is turned to the ON position when a current flows from the base (B) to the emitter (E). A much larger current can then flow from the collector (C) to the emitter (figure 3a).
- The transistor is in the OFF position when no current (or very little current) is flowing from the base to the emitter. No current can then run from the collector to the emitter (figure 3b).

figure 3 A schematic representation of a transistor in the ON (a) and OFF (b) positions.

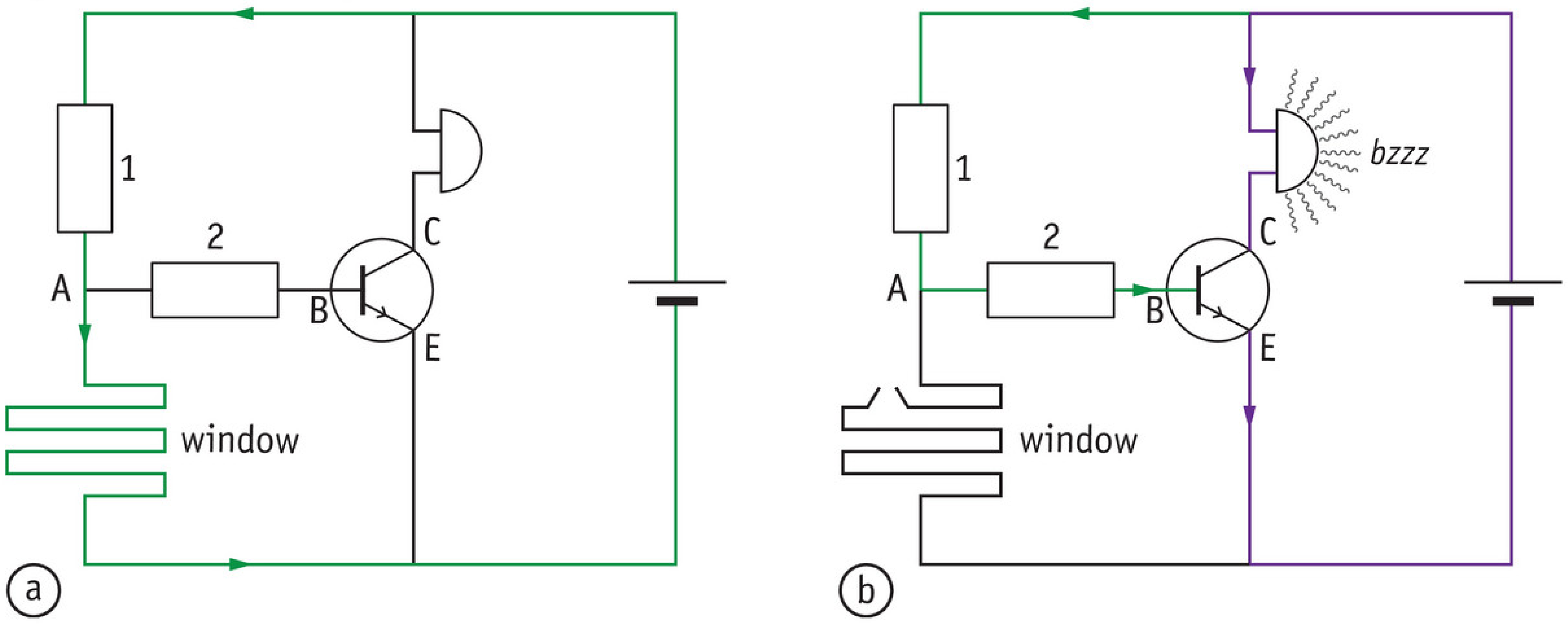


You therefore use a small 'switching current' (from B to E) to turn a much larger 'collector current' (from C to E) on and off. A transistor can easily get damaged if these currents become too large. That is why one or more resistors are often used in circuits with transistors. They work as current limiters.

A BURGLAR ALARM

Figure 4 shows a burglar alarm with a wire on a pane of glass. In this circuit, a wire on the window is used as a sensor. You can see that the current is splits into two at A (figure 4a). The bulk of the current (more than 99.9%) goes through the wire on the window back to the battery. Very little current runs through the base (because it has a much higher resistance).

figure 4 An alarm system with a transistor.



The size of the switching current through the base is the signal that the transistor responds to. As long as the wire on the window remains undamaged, the switching current will be very small and the transistor stays in the OFF position. No current runs from C to E then. The buzzer is off. Resistors 1 and 2 make sure that the currents that do flow are kept as small as possible.

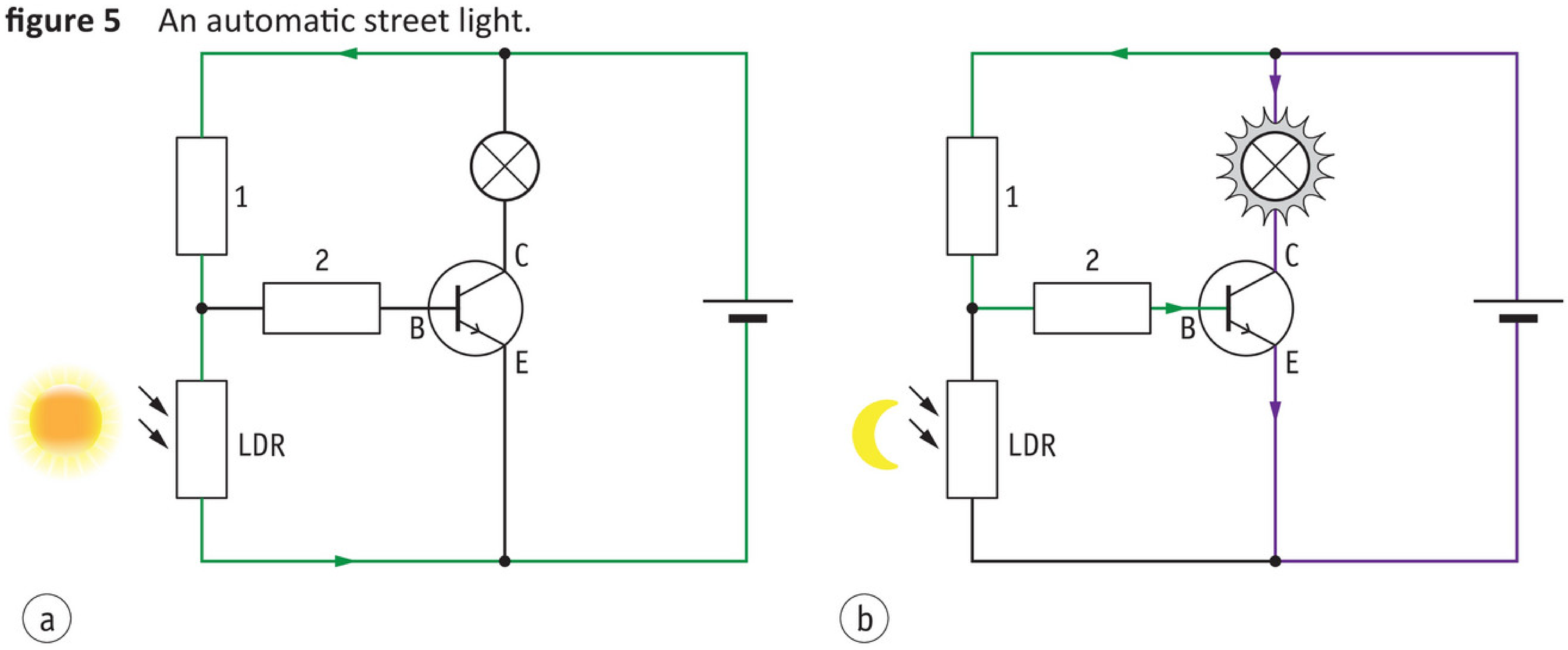
In figure 4b, someone has broken the window and the wire on the window is damaged. The current can only flow back to the battery via the base. The switching current from B to E will therefore be much larger. The transistor reacts to this signal by switching to the ON position. A large current can also flow from C to E now: the buzzer starts working.

AN AUTOMATIC STREETLIGHT

You can also use a transistor to build an automatic streetlight. You then replace two components in the circuit in figure 4a: the wire on the windscreen is replaced by an LDR and the buzzer by a lightbulb.
Figure 5a shows you the result. When it is light outside, the resistance of the LDR will be small. Almost all the current then flows through the LDR and not through the base. The transistor stays in the OFF position and the bulb is not lit.

When it is dark outside, the resistance of the LDR will increase. As a result, more and more current will flow through the base. More and more current will then flow through the bulb too. When it is completely dark, the bulb is fully lit (figure 5b).

figure 5 An automatic street light.



PLUS THE DIODE

In a computer or television, you find a lot of diodes as well as resistors. A **diode** is a special kind of resistor that the current can only flow through in one direction. Figure 6a shows the symbol for a diode. Diodes that emit light when current flows through them are called LEDs (figure 6b). If the current flows in the direction of the arrow, the diode is pointing in the forward direction. The diode then has a very low resistance and the current can flow through it easily (figure 7a). If the diode is pointing in the reverse direction, its resistance is very high (figure 7b). You say the diode has been connected in the reverse direction.

figure 6 The symbols for a diode (a) and a LED (b).

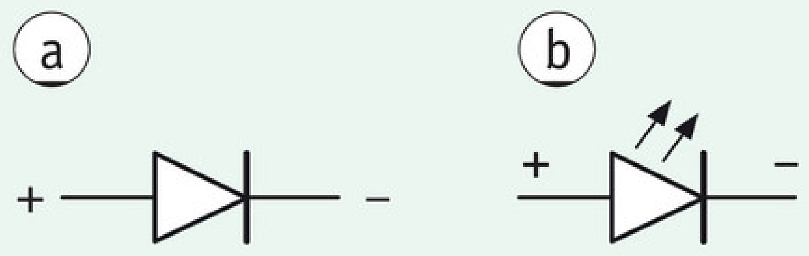
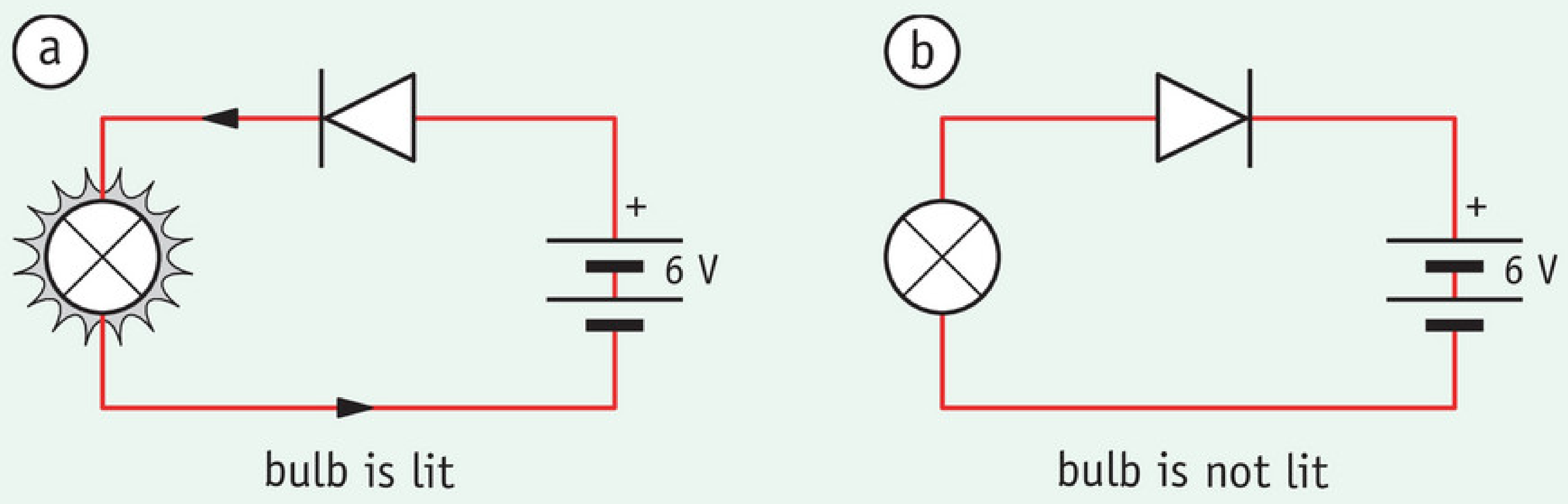


figure 7 How a diode works.



Diodes are used to convert alternating voltage into direct current. Sometimes you have an alternating voltage source and you need to convert that alternating voltage into direct voltage, for example in a phone charger. Figure 8 shows an example of a simple rectifier. Connecting up the diodes in a special way makes sure that the current can only flow in one direction through the LED and the resistor.

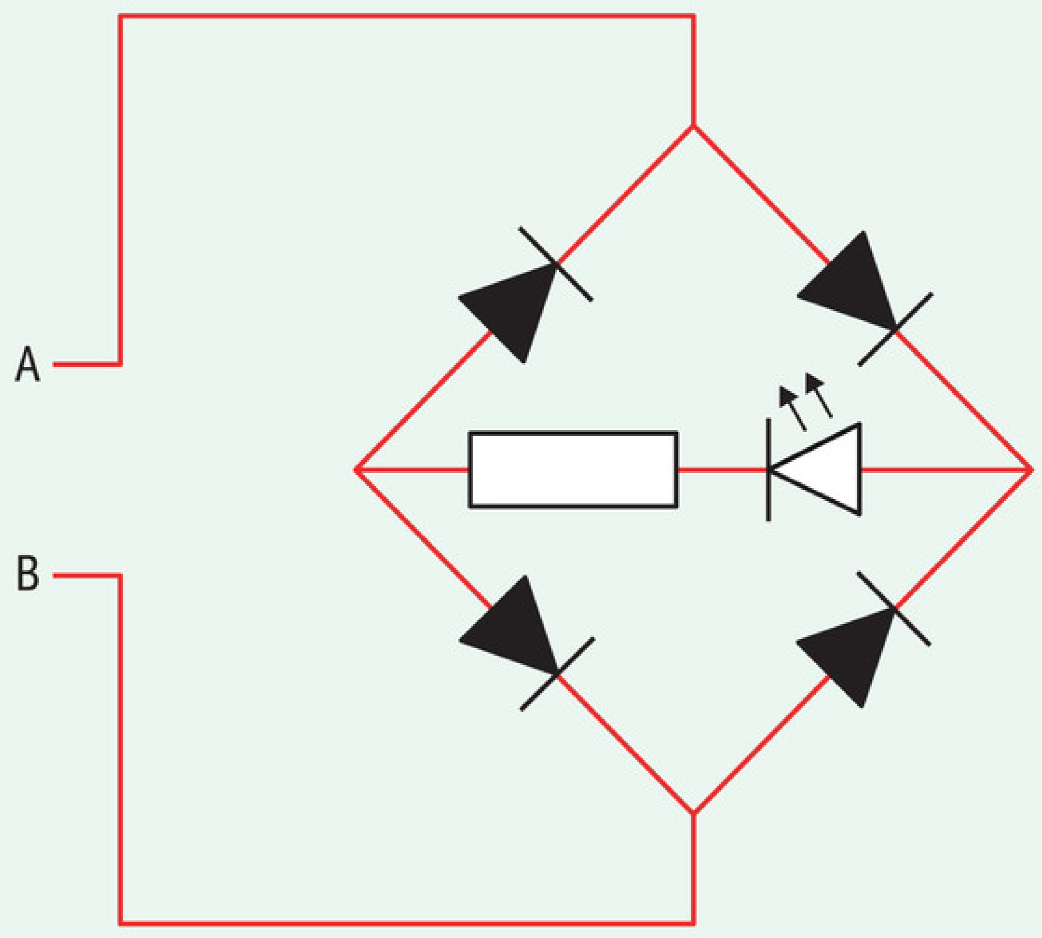


figure 8 A diagram of a rectifier.

Practice the concepts using the *Flash cards*.

COURSE MATERIAL

1

Answer the following questions.

a What is the purpose of the transistor in a burglar alarm?

b What are the names of the three connection points of a transistor?

c When will a transistor allow the collector current to pass?

d When will a transistor block the collector current?

2

Draw lines to connect the functions to the correct components.

function	components
	○ 1 electric motor
A sensor ○	○ 2 LDR
B switch ○	○ 3 LED light
C actuator ○	○ 4 NTC
	○ 5 transistor
	○ 6 buzzer

IN PRACTICE

3

You can find all kinds of automatic circuits in a home.
Which automatic circuits:

a play a role in protecting the domestic electricity supply?

b regulate the temperature in the various rooms in the house?

c help to protect a house from intruders?

d let an appliance perform a series of actions automatically?

4

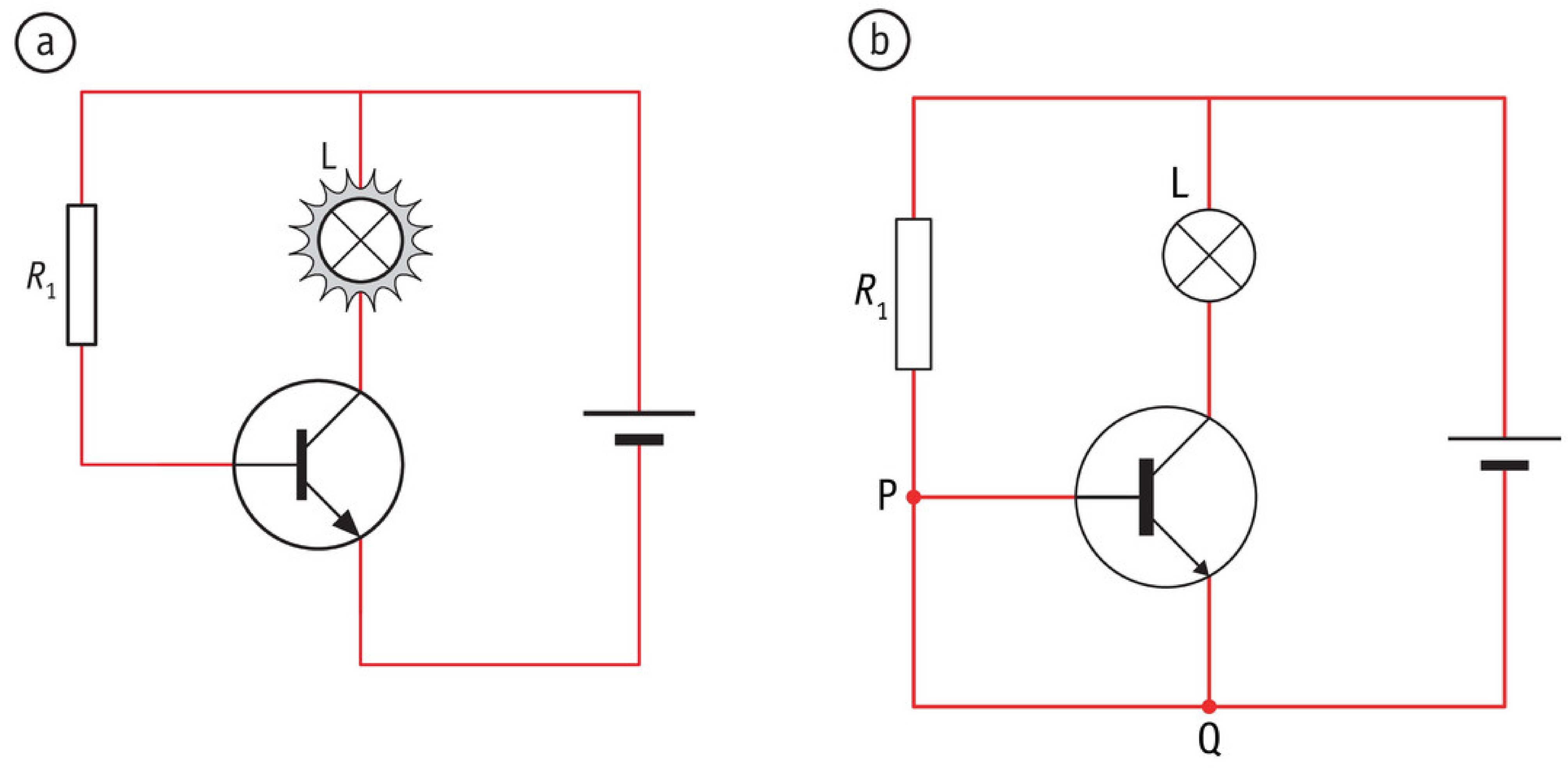
Inez has made a test circuit with a transistor (figure 9a).

a In figure 9a, put a B next to the base, a C next to the collector and an E next to the emitter of the transistor.

b Explain which current is larger: the one through the bulb or the one through the resistor.

c Inez adds a wire to her circuit from P to Q (figure 9b).
Explain why the bulb now goes out.

figure 9 Inez's circuits.



5 A certain type of burglar alarm uses a light gate to detect people. The light gate consists of a light source that produces a narrow beam of light, plus a light sensor. If a burglar (or anyone else) breaks the beam, the alarm will be set off. Figure 10 shows a drawing of a light gate.

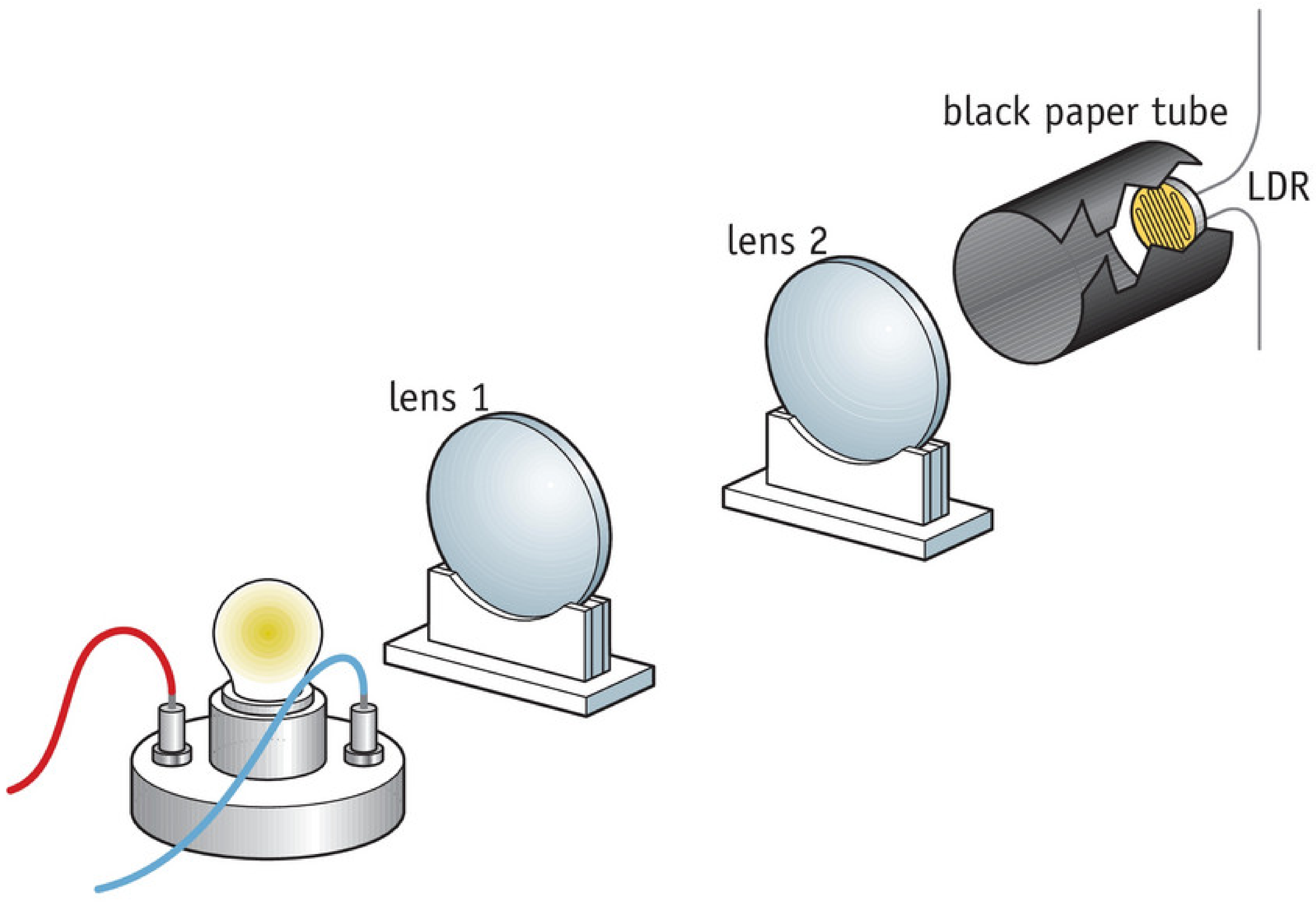


figure 10 A model of a light gate.

a Explain:

- what lens 1 is used for;
- what lens 2 is used for.

b Make a simple burglar alarm that can sound a buzzer when the beam is broken. Draw the circuit diagram for the alarm.

c You can also construct this alarm using an infrared laser and an infrared sensor. Explain the advantage of using infrared radiation for a burglar alarm.

★ 6

The circuit in figure 5 has a disadvantage: you can't turn the lighting on when it is still light outside. You can solve this problem if you use a normal switch and two wires.

a Explain whether you have to connect the transistor and the normal switch in series or in parallel for this.

b In figure 11, draw the circuit diagram for the modified circuit that also lets you turn on the lighting during the daytime.

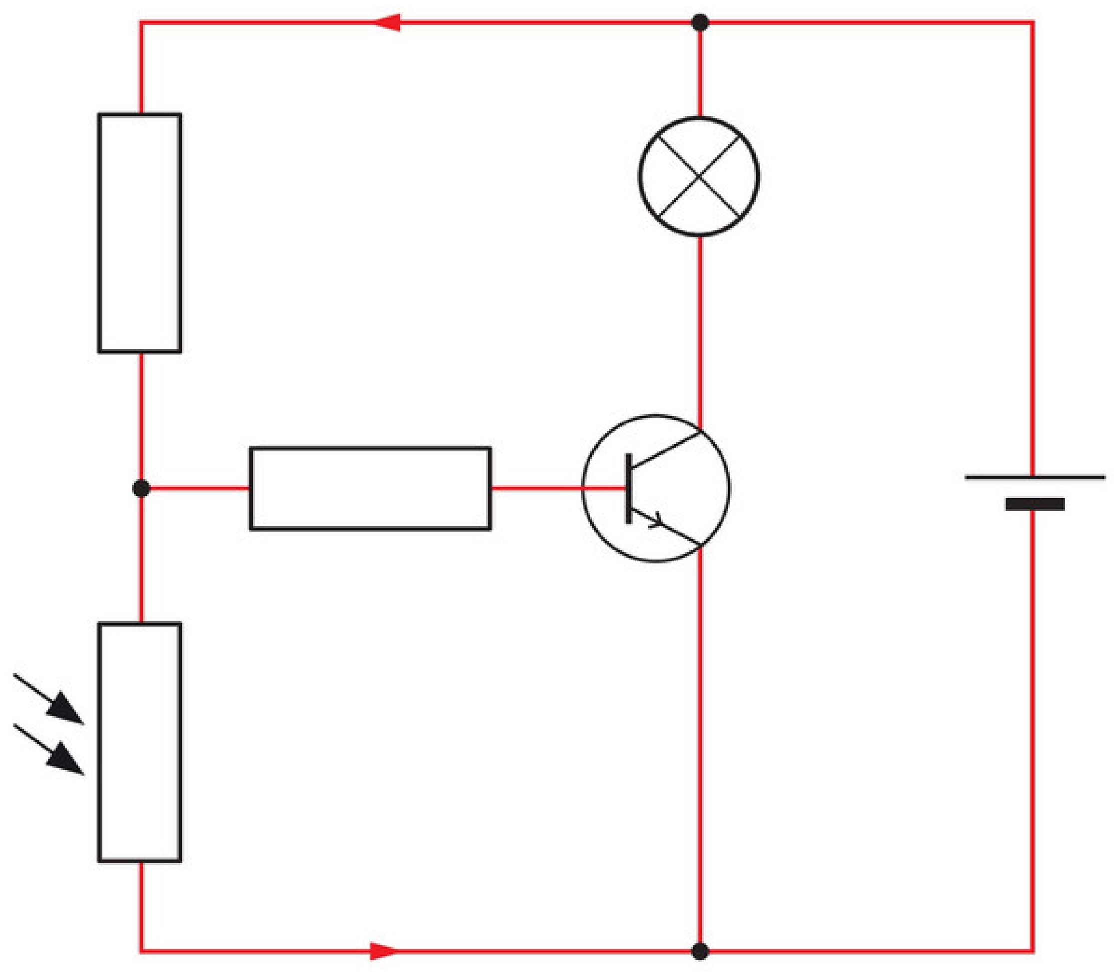


figure 11 The modified circuit that also lets you turn on the streetlight during the daytime.

7

Computer chips can get very hot. That is why most computers have a fan that blows cool air across the chips. The circuit in figure 12 can automatically control the speed of the fan.

a Explain which circuit component in this circuit is acting as a sensor.

b Work out how this circuit reacts when the temperature increases.

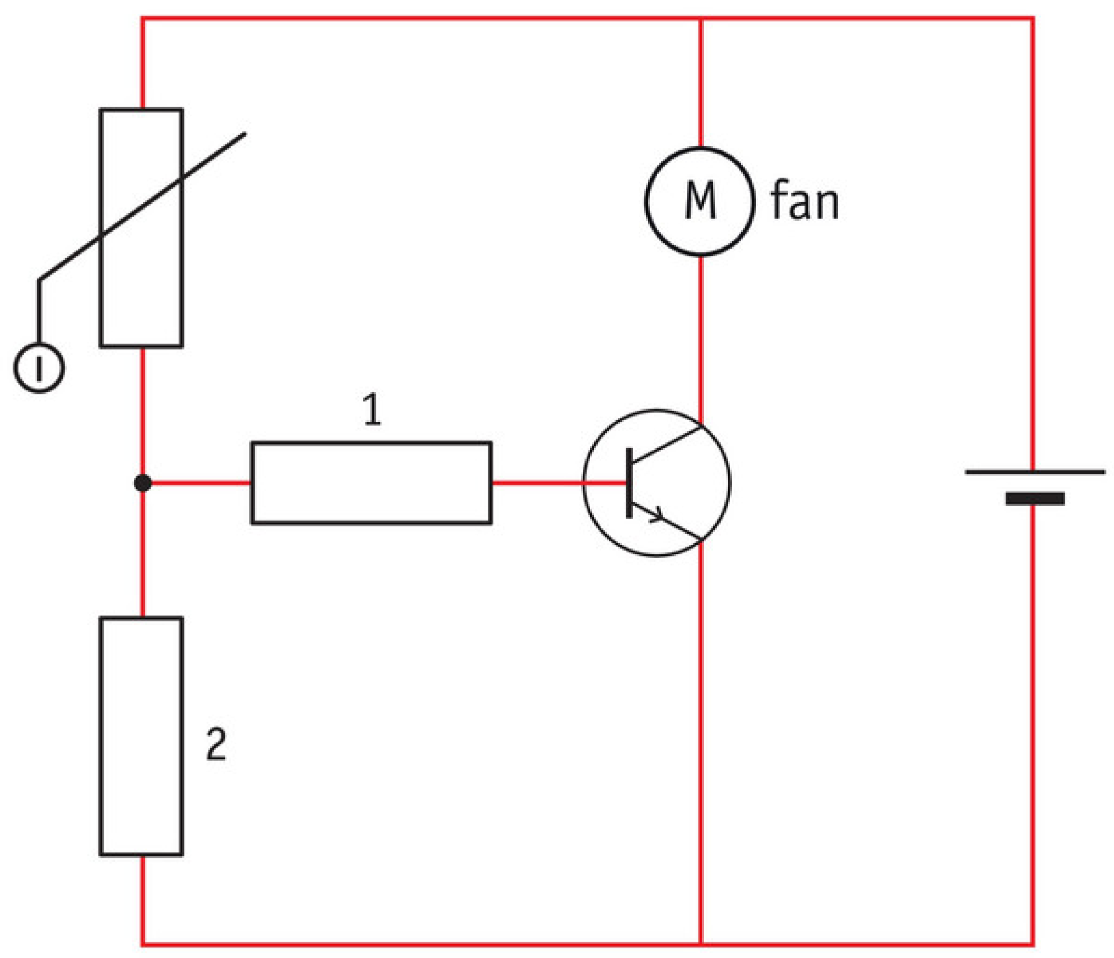


figure 12 A fan that responds to the temperature.

8

Two resistors are used in the circuit in figure 12: resistor 1 and resistor 2.

a Explain which resistor is used to limit the current through the sensor.

b Which current is limited by the other resistor?

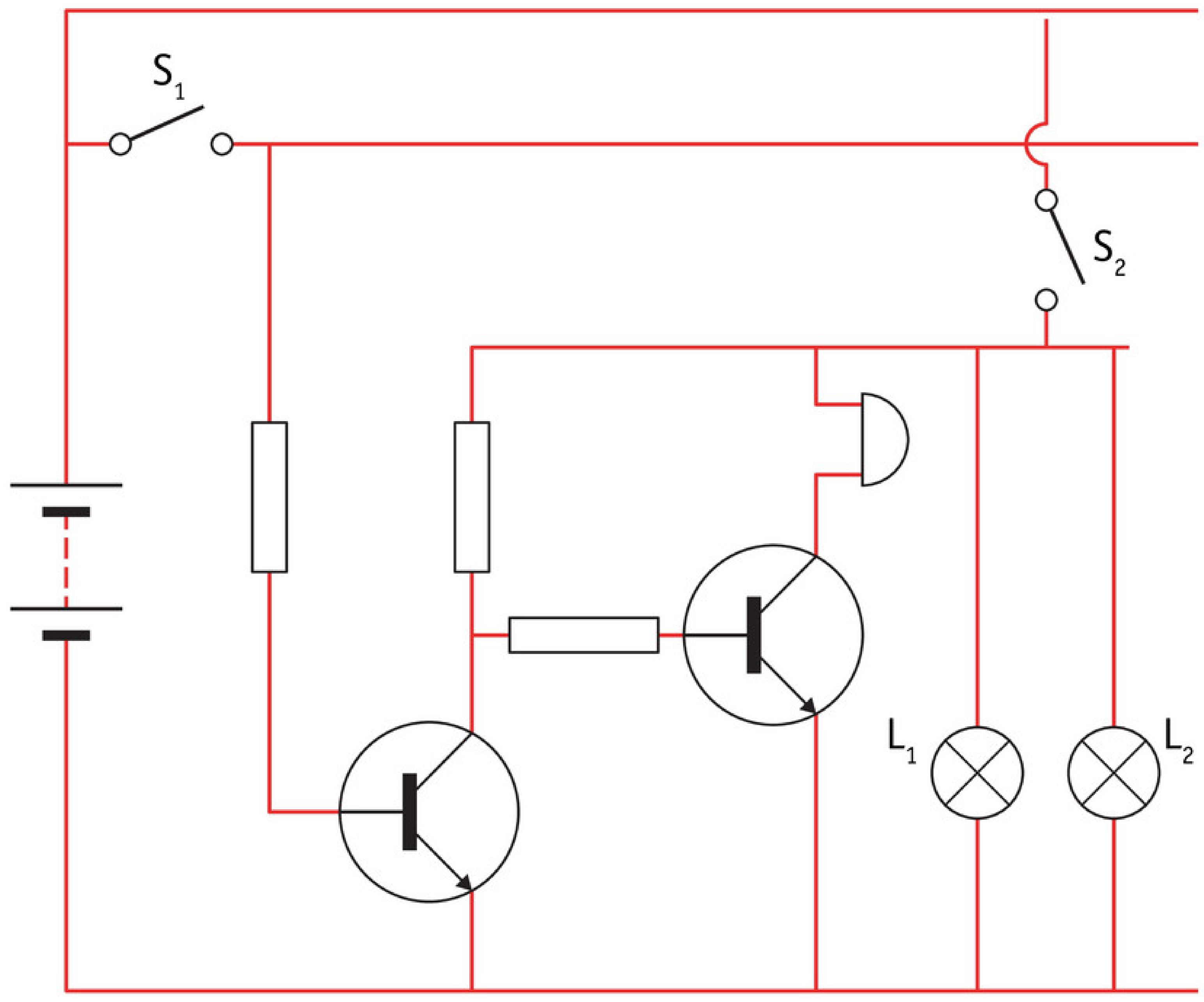
★ 9

Figure 13 shows a design for protecting a battery. The aim of this protection is to stop the driver leaving the car with the lights on so that the battery runs out.

a How is the driver warned that the lights are still on?

b In what situation should this circuit give a warning? Mention the switches S_1 and S_2 in your explanation.

c Explain why the buzzer starts to make a sound in this situation (but not otherwise).



S_1 = ignition
S_2 = headlight switch

figure 13 A battery protection system.

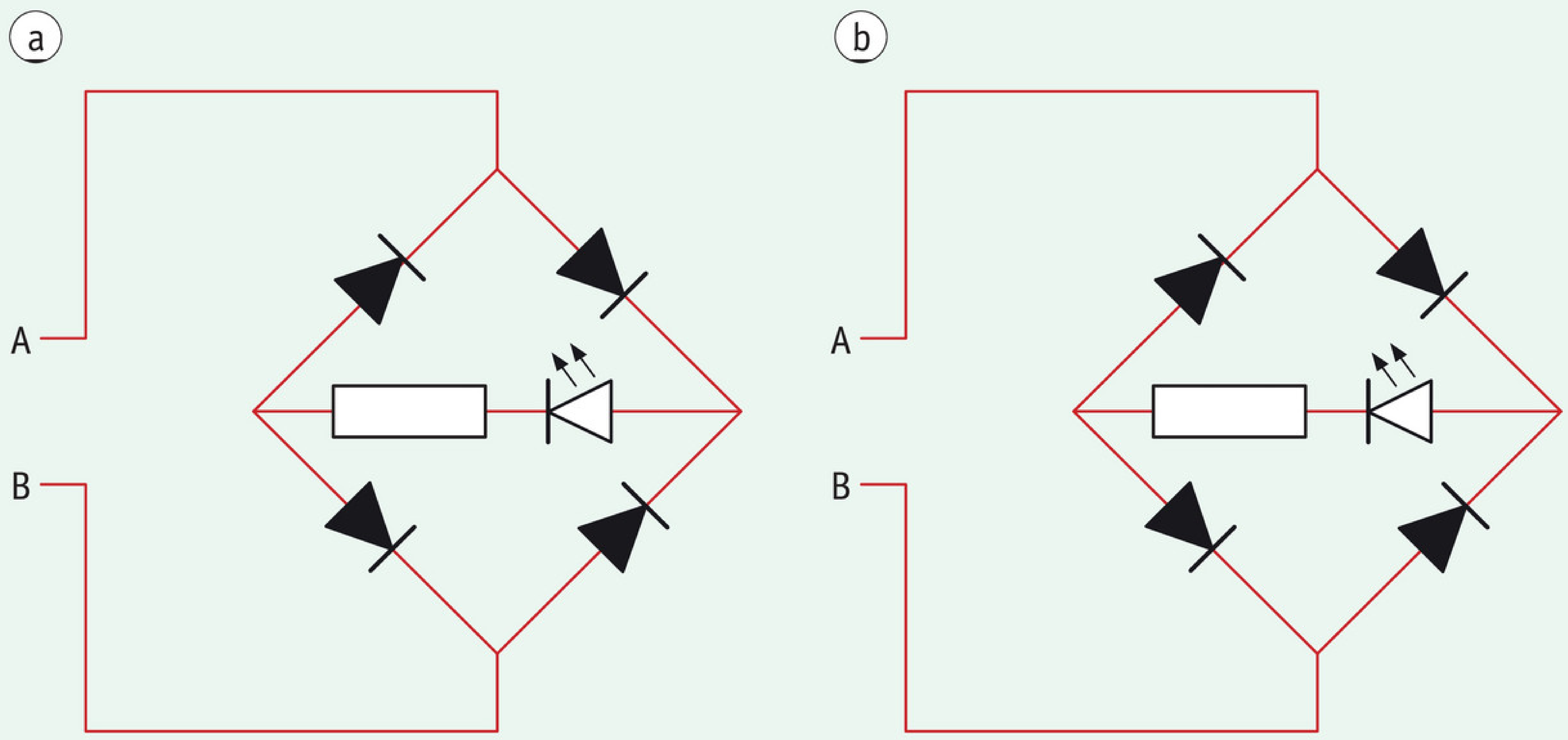
Test what you know with *Test yourself*.

PLUS THE DIODE

10 Figure 14 shows diodes used as a rectifier. An alternating voltage has been connected between points A and B. At this moment in time, point A is the positive terminal and point B is the negative terminal.

- **a** In figure 14a, use a red pen to draw the path that the current takes from point A to point B.
- **b** A little later, point A is the negative terminal and point B the positive terminal. In figure 14b, use a green pen to draw the path that the current now takes from point A to point B.
- **c** Explain how the circuit works as a rectifier and why the LED will be lit in both the situation in (a) and the situation in (b).

figure 14 The current through the rectifier.



11 Figure 15 shows the (I,U) diagram for a diode. As you can see, the diode in the forward direction will only start conducting current from a certain voltage value. This voltage is called the forward voltage. In the graph, it is roughly equal to 0.85 V. Assume that this curve applies to the diodes and LED used in figure 14. At a certain moment, the voltage between points A and B is 6.0 V.

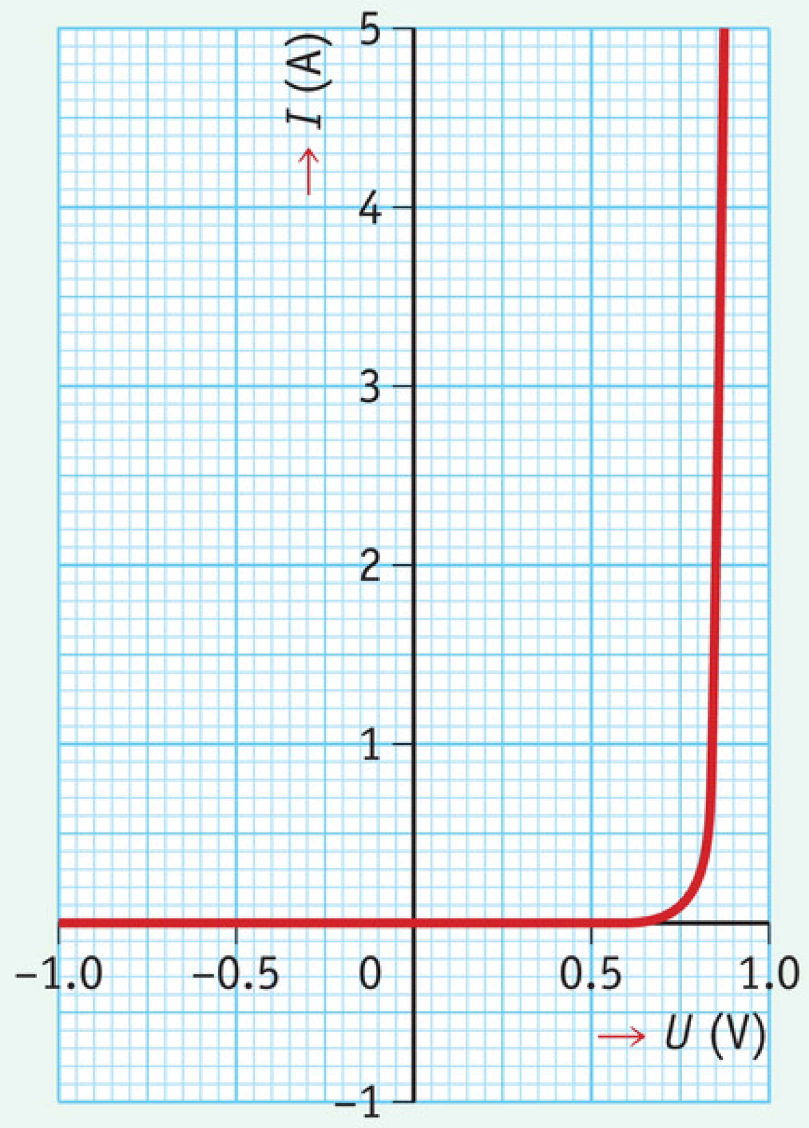


figure 15 The (I,U) diagram of a diode.

- **a** Explain how large the voltage is across the resistor in this case.
- **b** Explain what would happen in this situation if you were to remove the resistor in figure 14 and replace it with switch wire.
- **c** Khatira connects up the LED in figure 14 in the opposite direction. Explain what you need to change in the circuit in order to make sure that the LED still lights up (using the alternating voltage).

Experiments

EXPERIMENT 1 THE (I,U) DIAGRAM OF A CONSTANTAN WIRE

40 minutes

Introduction

When you change the voltage in a circuit, the current changes too. You can make measurements to find out how exactly the current changes. You increase the voltage step by step, check how large the current has become every time.

Aim

The question you are studying is:
What is the relationship between the current and the voltage in a constantan wire?

Requirements

- ☐ power supply box
- ☐ 5 wires
- ☐ ammeter or multimeter
- ☐ voltmeter or multimeter
- ☐ constantan wire

Doing the experiment and writing it up

Measuring

- See the skills section on *Working with measuring instruments*.
- Make the circuit shown in figure 1.

If you need more practice in *Making electrical circuits*, go to the *Skills Trainer*.

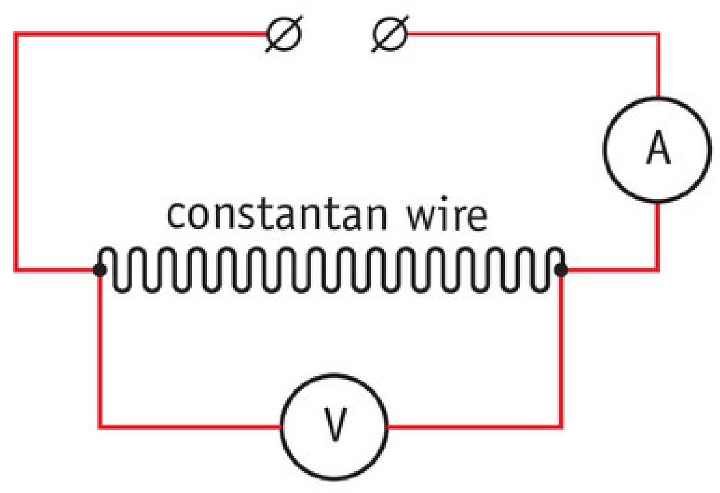


figure 1 The circuit for Experiment 1.

- Set the voltage to 0 V before you switch on the supply.
- Increase the voltage in steps of 0.5 V and measure the corresponding current through the wire. Keep going until the voltage is 3.0 V.

1 Write down your measurement data in the correct place in table 1.

table 1 The measurements for Experiment 1.

voltage (V)	current (A)	resistance (Ω)
0		
0.5		
1.0		
1.5		
2.0		
2.5		
3.0		

Writing up

2 In figure 2, use your measurements to draw a graph as an (I,U) diagram.

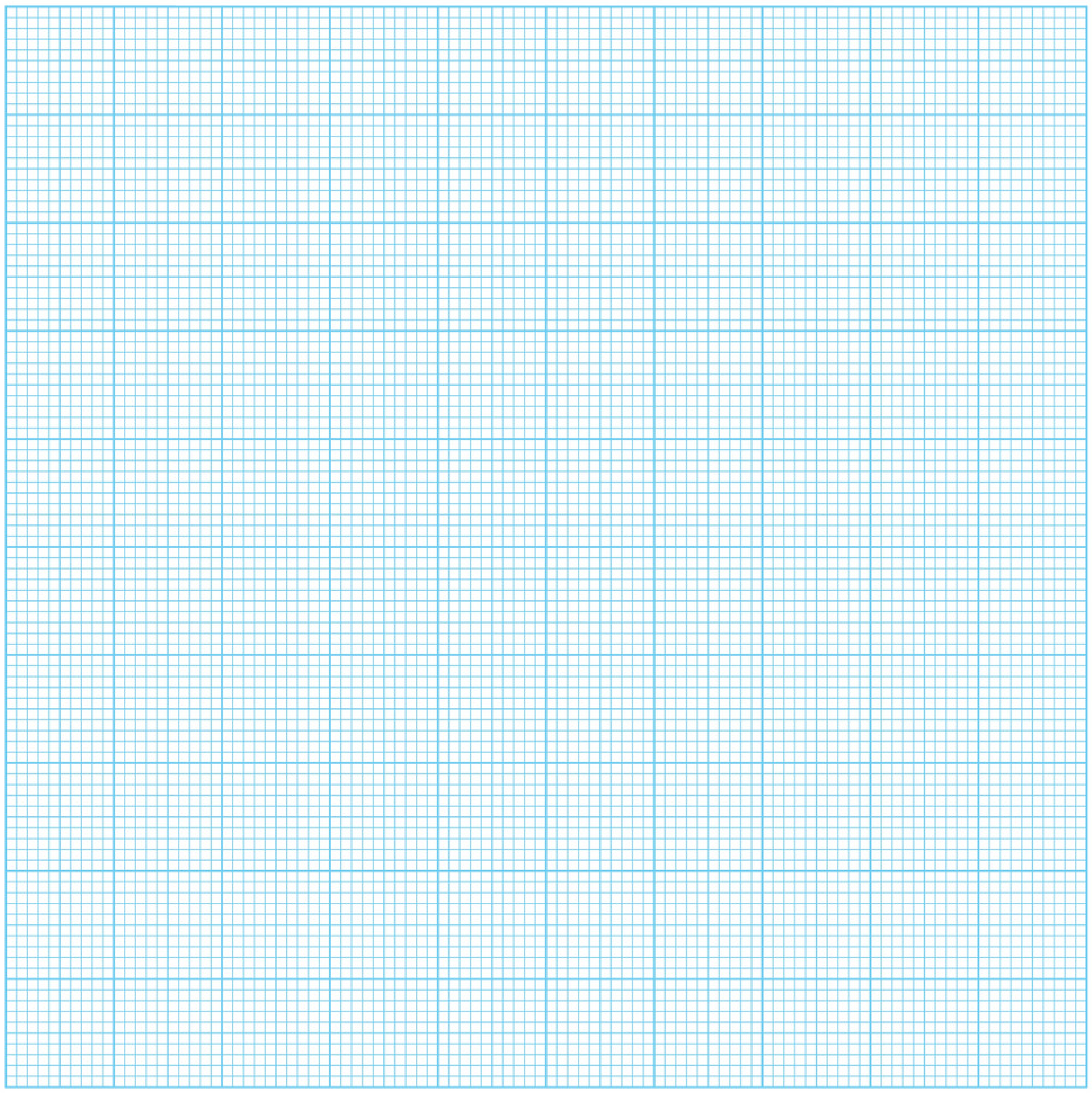


figure 2 The relationship between the current through a constantan wire and the voltage across it.

3 What can you say about the relationship between the voltage *across* the wire and the current *through* the wire?

4 Calculate the resistance of the wire for each measurement. Write the results down in the third column of table 1.

5 What do you notice when you compare the calculated resistance values against each other?

....

....

....

....

6 Could you have drawn the same conclusion as from Exercise 5 from the diagram? Explain your answer.

....

....

....

....

....

EXPERIMENT 2 THE (I,U) DIAGRAM OF A BULB

30 minutes

Introduction
When you change the voltage in a circuit, the current changes too. The current in a constantan wire is proportional to the voltage: the two variables move up and down together. Does the result of Experiment 1 apply for other types of wire, though?

Aim
The question you are studying is:
What is the relationship between the current and the voltage of a filament?

Requirements
- ☐ power supply box
- ☐ 5 wires
- ☐ ammeter or multimeter
- ☐ voltmeter or multimeter
- ☐ light bulb (6 V)
- ☐ holder

Doing the experiment and writing it up

Measuring

- Make the circuit shown in figure 3.
- Set the voltage to 0 V before you switch on the supply.
- Increase the voltage in steps of 1 V and measure the corresponding current through the bulb. Keep going until the voltage is 6 V.

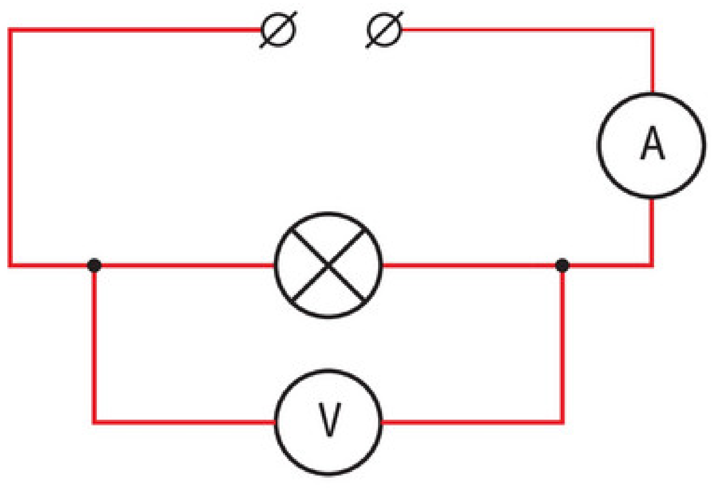


figure 3 The circuit for Experiment 2.

1 Write down your measurement data in the correct place in table 2.

table 2 The measurements for Experiment 2.

voltage (V)	current (A)	resistance (Ω)
0		
1.0		
2.0		
3.0		
4.0		
5.0		
6.0		

Writing up

2 In figure 4, use your measurements to draw a graph as an (I,U) diagram.

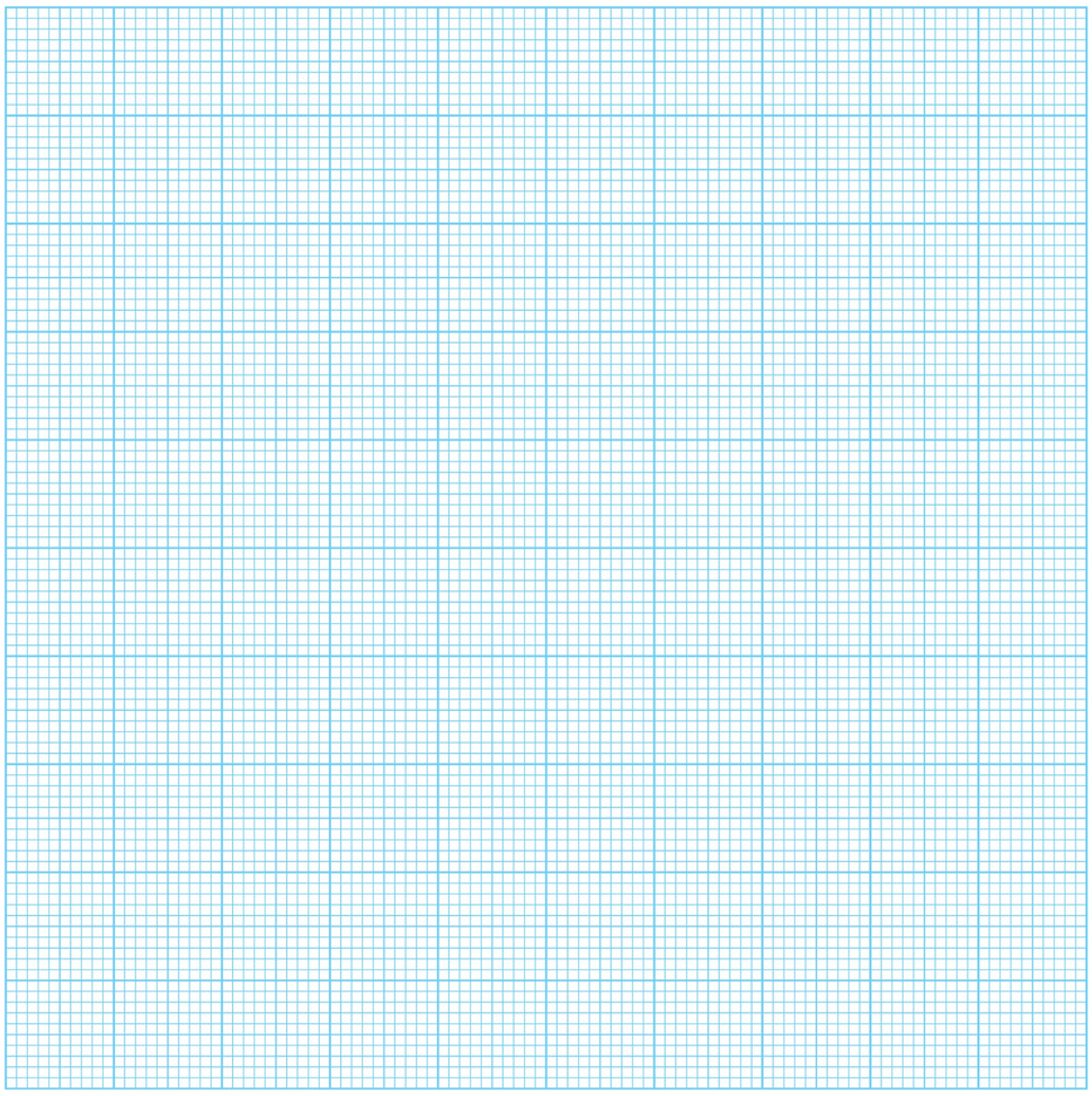


figure 4 The relationship between the current through an incandescent bulb and the voltage across it.

3 What can you say about the relationship between the voltage *across* the wire and the current *through* the wire?

....

....

....

....

4 Calculate the resistance of the incandescent bulb for each measurement. Write the results down in the third column of table 2.

5 What do you notice when you compare the calculated resistance values against each other?

....

....

....

....

EXPERIMENT 3 THE EQUIVALENT RESISTANCE OF A SERIES CIRCUIT

20 minutes

Introduction

Resistors are often connected in series. The following applies to the total resistance R_{tot} of such a circuit:

$R_{tot} = R_1 + R_2 + ...$

Aim

You are going to check the formula $R_{tot} = R_1 + R_2 + ...$ in a series circuit consisting of two resistors.

Requirements

- ☐ power supply box
- ☐ 6 wires
- ☐ voltmeter
- ☐ ammeter
- ☐ 2 resistors

Doing the experiment and writing it up

Measuring

- Determine the values for resistor 1 and resistor 2 using a circuit with the ammeter and voltmeter.

1 Write your measurements and calculations down.

....

....

....

....

....

- Make the circuit shown in figure 5.
- Measure the (total) voltage and the current.

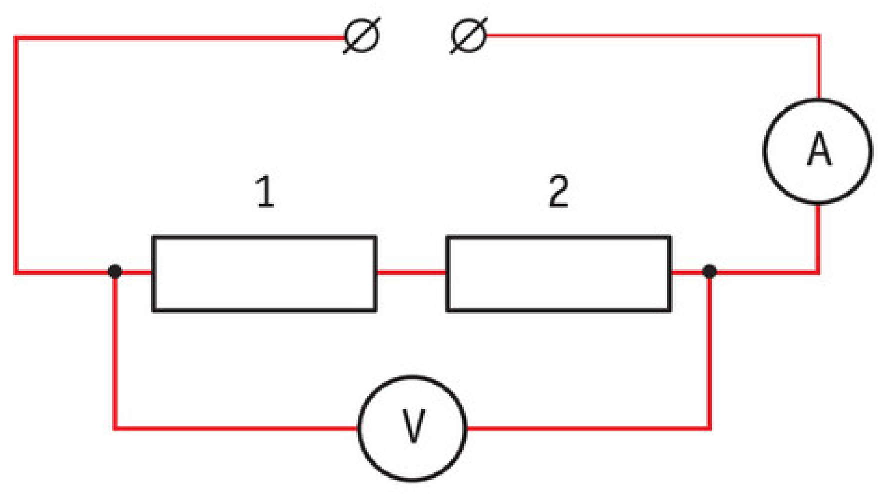


figure 5 The circuit diagram for Experiment 3.

2 Write down your measurement results.

....

....

....

....

Writing up

3 Calculate the total resistance using the formula:

$$R_{tot} = \frac{U_{tot}}{I}$$

....

....

....

....

4 Calculate the total resistance using the formula:
$R_{tot} = R_1 + R_2$

....

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....

5 Compare the answers to exercises 3 and 4.
What conclusion can you draw?

....

....

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....

....

EXPERIMENT 4 THE EQUIVALENT RESISTANCE OF A PARALLEL CIRCUIT

20 minutes

Introduction

In Experiment 3, you calculated the equivalent resistance of two resistors that were connected in series. In this experiment, you are going to work with the same resistors, but now you connect them in parallel.

Aim

For a parallel circuit with two resistors, you will be checking the formula:

$$\frac{1}{R_{tot}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$$

Requirements

- ☐ power supply box
- ☐ 6 wires
- ☐ voltmeter
- ☐ ammeter
- ☐ 2 resistors

Doing the experiment and writing it up

1 Write down the values for resistors 1 and 2 from Experiment 3.

....

....

Measuring

- Make the circuit shown in figure 6.
- Measure the voltage and the (total) current.

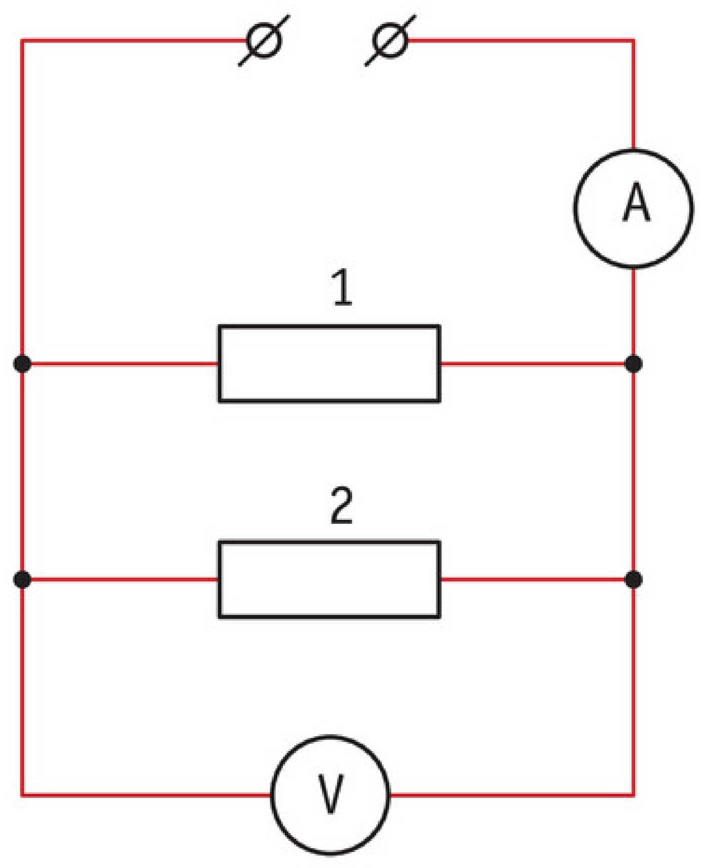


figure 6 The circuit for Experiment 4.

2 Write down your measurement results.

....

....

....

....

Writing up

3 Calculate the total resistance using the formula:

$$R_{tot} = \frac{U}{I_{tot}}$$

....

....

....

....

4 Calculate the total resistance using the formula:

$$\frac{1}{R_{tot}} = \frac{1}{R_1} + \frac{1}{R_2}$$

....

....

....

....

5 Compare the answers to exercises 3 and 4.
What conclusion can you draw?

....

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....

6 According to the theory, the total resistance in a parallel circuit is lower than both R_1 and also lower than R_2.
What about this parallel circuit?

....

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Weirdly fast: the quantum computer



A hospital in 2040. A doctor has just established what your problem is. “There’s no reason for you to worry,” she says. “Now I’m going to let our computer work out what the treatment should be.” You nod, because that is the standard procedure. The computer chooses the treatment that is best for you based on thousands of pieces of data about your body and life history. An appropriate medicine will be made for you if that is necessary. You could almost forget it used to be different in the past...

Unfortunately, 2040 is still a long way off. If people become ill now, they usually get a standard treatment based on the average characteristics of the patient group. Doctors know this is not ideal but there is simply no other option. One of the problems is that computers can’t calculate things fast enough. It would take years to combine all the data and come up with a customised treatment. You can’t wait for that.

But it looks as if this is about to change. Scientists and technology companies like Google and IBM are working hard on developing a quantum computer. This kind of computer would take only a few minutes to do calculations that would take ordinary computers hundreds of years. That will make all kinds of new applications possible, such as personalised medicine: medicine that is tailored to suit the individual patient.

BILLIONS OF TRANSISTORS

Quantum computers are still in the experimental stage. Only ‘ordinary’ computers are used in daily life. They can look very different, from ultrathin smartphones to metres-high mainframes in the computing centres of large companies. Even so, all those different computers are based on the same basic idea: transistors – tiny electronic switches that can be on or off – are used to process and store information.

You can buy individual transistors, but not the transistors in computers. A computer transistor is a microscopic area on a computer chip that has been processed in a special way. That single chip has lots more transistors, other electronic components and connecting wires. Together, they form one extensive, complex electronic circuit, known as an integrated circuit or IC.

Chip makers have come up with all kinds of ways of getting more and more transistors onto a chip. As a result, the number of transistors on a chip has grown enormously. There were about a thousand in 1970, a million in 1990 and a billion in 2010 (figure 1). The computing power of computers has grown as a result. But the end is in sight for this approach. You can't make transistors much smaller than they already are. To make computers faster still, you need a different approach.

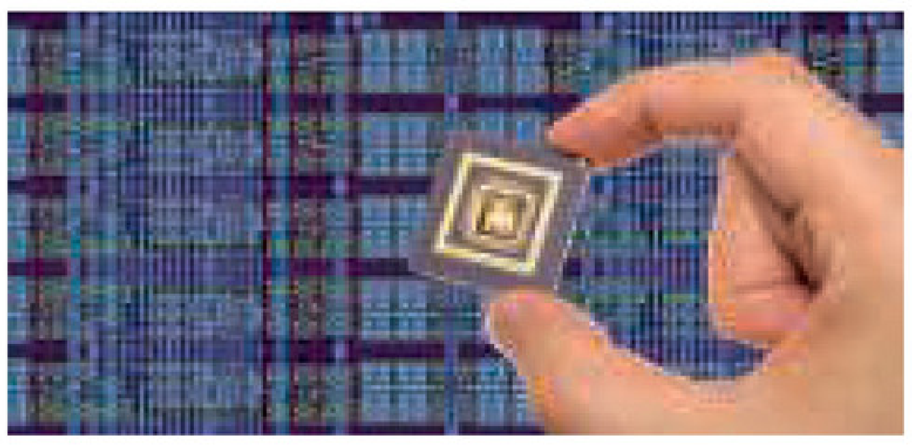


figure 1 A microchip with billions of transistors.

QUANTUM COMPUTING

That is why tech companies are investing in new concepts such as the quantum computer. In theory, a quantum computer should be much faster at doing calculations than an ordinary computer. It remains to be seen whether that is the case in reality: building a quantum computer that you can use in practice is a huge challenge. But researchers are making progress. Simple test versions have been built proving that the concept works in principle.

The key characteristic of a quantum computer is that it can try out different possibilities at the same time. If you are trying to find your way out of a maze, you take different routes one by one until you find the one route that gets you to the exit. You can write a computer program for that which basically does the same thing. But a quantum computer can look at all the possible routes at the same time, so it can find the exit much more quickly.

Finding the best route is often very important in practical situations. Take the example of a delivery company that has to deliver thousands of parcels every day. That company wants as efficient a solution as possible when allocating the parcels to the various delivery vans and deciding on the routes the vans should take (figure 2). But the number of different possibilities gets so huge that ordinary computers soon can't cope. A quantum computer can do that much better in principle.

SUPERPOSITION AND ENTANGLEMENT

Quantum computers are very different from ordinary computers. You can see that from the way they deal with information. In an ordinary computer, the smallest unit of information that the computer can process is the *bit*: a signal with the value 0 or 1 (figure 3). That is the form in which the transistors are best able to process the information. One bit is enough to store whether someone has answered 'yes' or 'no', or whether they want a single train ticket or return ticket. If you have more information, you need more bits.

The smallest unit of information in a quantum computer is the *qubit*, short for *quantum bit*. But a qubit behaves quite differently to a bit. A bit is quite clear: it can have the value 0 or the value 1. A qubit can be put in a position that physicists call a *superposition* of 1 or 0: it is neither 0 nor 1, but it can be either with a certain probability. The role played by this chance element is a key characteristic of *quantum computing*.

Qubits have a second, equally weird property. The bits in an

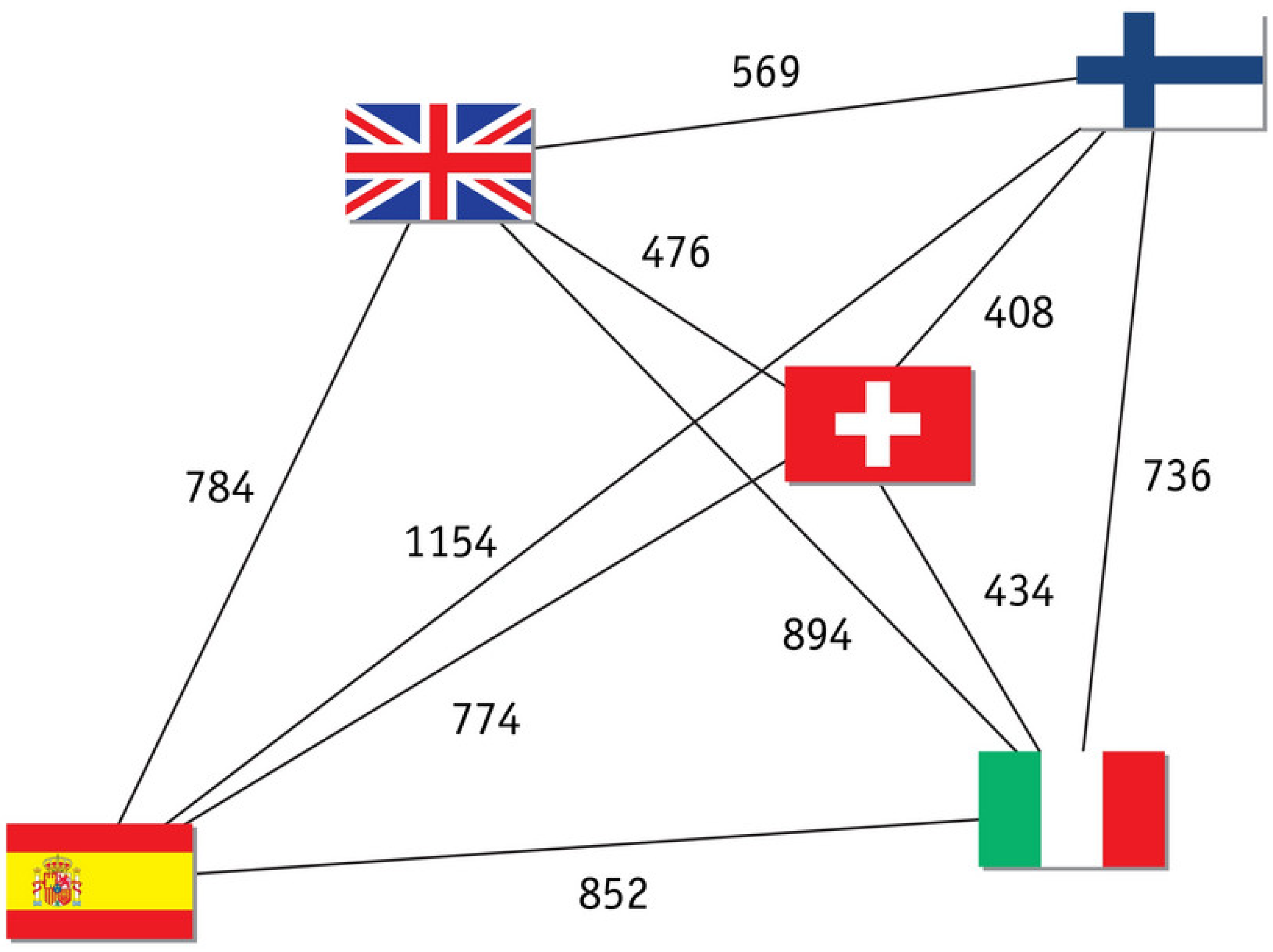


figure 2 What is the optimum route for visiting all these five places?



figure 3 Ordinary computers use bits.

"A quantum computer can look at an incredible number of possibilities at the same time and select the best option."

ordinary computer each have their own value (0 or 1), regardless of the other bits. The qubits in a quantum computer are *entangled* with each other: they share superposed states with each other. This combination of superposition and entanglement lets a quantum computer look at an incredible number of possibilities at the same time and select the best option.

THE COMPUTER OF THE FUTURE?

Qubits are much more versatile than bits but they are also fragile. They need to be properly shielded from the outside world or else they lose their superposition and entanglement. Any disruption to their interaction is fatal. Researchers therefore have to cool their samples with qubits down to just above absolute zero so that they are not affected by the thermal agitation of the atoms around them.

It looks at the moment as if quantum computers will not become everyday devices. The technology is too complex for that. Anyway, you don't need their enormous computing power for everyday tasks. It would be best to keep quantum computers for problems that ordinary computers can't handle.

People will still be using ordinary computers a lot in 2040. They are reliable, cheap and powerful enough for many purposes. It is open to question whether quantum computers will be widely available by then. But if they are available, it will probably only be possible to use them remotely via the Internet or another network. They can still change your life even then – for example, by finding that one medical treatment that would fit you perfectly (figure 4).



figure 4 Computers are already indispensable for doctors.

EXERCISES

1 An automatic weather station collects information about the weather such as the temperature and wind direction. This information is coded in bits and then stored in the computer's memory.

- **a** You need just two bits to record four wind directions. One possible code is N = 00, E = 01, S = 10 and W = 11. How many wind directions can you record if you have three bits available?
- **b** Work out how many bits you need to record the wind directions on the compass rose in figure 5.
- **c** Work out how many bits you need to record the wind directions to the nearest 1°.

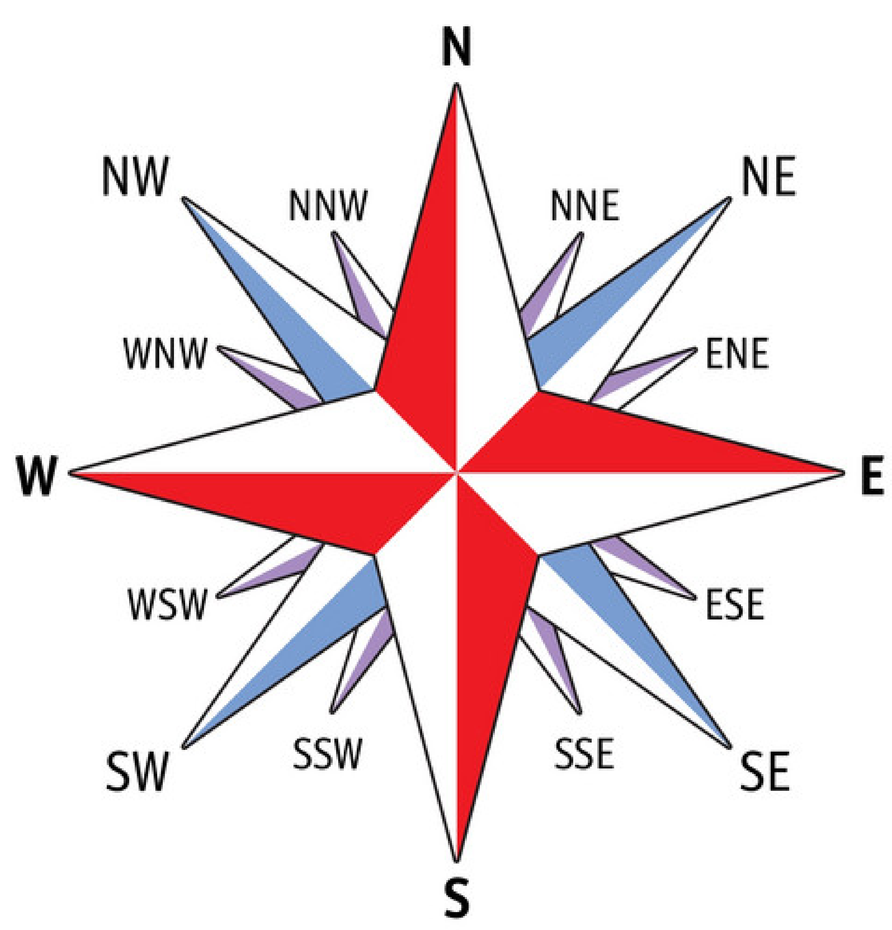


figure 5 A compass rose.

2

The travelling salesman problem (or TSP) is a well-known problem in computer science. In this problem, a number of towns are given with the distances between them. You need to find the shortest route in which you pass through each town once and end up in the town you started in.
Table 1 gives five towns. One possible route is: Amsterdam – Groningen – Maastricht – Utrecht – Zwolle – Amsterdam: 189 + 336 + 180 + 91 + 119 = 915 km

table 1 Distances between five towns.

		distance (km)
Amsterdam	Groningen	189
Amsterdam	Maastricht	214
Amsterdam	Utrecht	59
Amsterdam	Zwolle	119
Groningen	Maastricht	336
Groningen	Utrecht	188
Groningen	Zwolle	105
Maastricht	Utrecht	180
Maastricht	Zwolle	231
Utrecht	Zwolle	91

a Work out how many routes there are in total for five towns.
b Determine the shortest route. Write down the towns in the correct order and put the number of kilometres between them.
c What problem did you run into when answering Exercise (b)?
d If the number of towns becomes too big, ordinary computers are no longer able to calculate a solution.
Explain why quantum computers are more suitable in theory for solving problems like this.
e Finding the most efficient routes can be very important in practice.
Write down two practical applications where that is the case.

3

Go to www.quantum-inspire.com. This website lets everyone learn more about quantum computing. Use it to find answers to the following questions.
a In what two ways can you get to know more about quantum computing in this website?
b What can you do with the editor and the simulator on the site?
c What benefit could you get from registering with this website?
d Why do the people who made this website want to get you interested in quantum computing?

Course material overview

5.1 CHARGE AND VOLTAGE

REMEMBER

- You can charge an object made of PVC electrically by rubbing it with a woollen cloth.
- You can tell that an object is charged because it attracts other objects. You can see, feel and hear the sparks jumping across.
- There are two kinds of charge: positive charge and negative charge. Charges of the same kind repel each other. Opposite charges attract one another.
- Only the negatively charged electrons can move from one object to another object. A negatively charged object has a surplus of electrons. A positively charged object has a shortage of electrons.
- There is a voltage between a negatively charged object and a positively charged object. If the two objects are connected by conductive material, an electric current flows. If there is a high voltage between a charged object and its environment, sparks may jump across to allow the charged object to discharge.
- Batteries and dynamos are voltage sources. They can produce current for a long time while keeping the voltage constant.
- You can calculate the total charge that flows through a wire using the formula $Q = I \cdot t$

CONCEPTS

electrically charged
The situation in which an object has an electrical charge.

electron
Negatively charged particle.

negative charge
The charge that a neutral object gets when it takes up electrons.

neutral
The situation in which the positive charge of an object is equal to the negative charge.

positive charge
The charge that a neutral object gets when it loses electrons.

proton
Positively charged particle.

statically charged
The situation in which an object has an electrical charge.

voltage
A measure of how much electrical energy each particle is carrying.

5.2 RESISTANCE

REMEMBER

- If it is difficult for current to flow through an object, that device has a high resistance.
- You can calculate the resistance (R), the voltage (U) and the current (I) with the formula $R = \frac{U}{I}$
- If the voltage across a component and the current through the component are directly proportional, the resistance does not change; we say then that the object satisfies Ohm's Law.
- Sometimes, the temperature of an object increases when a current flows through it. As a result, the current is not able to flow through the object so easily. The resistance of the object increases. Ohm's Law no longer applies. If the temperature increase is limited, you can ignore the increase in resistance.
- As the temperature of an NTC increases, its resistance becomes lower. The NTC then lets more current through.
- If more light falls on an LDR, its resistance becomes lower. The LDR then lets more current through.
- An adjustable resistor consists of a rolled-up wire and a slide that lets you set the size of the resistance.

CONCEPTS

(I,U) diagram
Graph showing the current against the voltage.

LDR
A variable resistor that is sensitive to changes in the amount of light.

NTC
A variable resistor that has a higher resistance when the temperature is lower.

Ohm's Law
The rule that says the voltage (across the wire) and the current (through the wire) are directly proportional.

ohmic resistance
Resistor where the resistance is the same regardless of the voltage.

resistance
The property of a component that determines how easily electrical current flows through it.

5.3 CONNECTING RESISTORS

REMEMBER

- A 'resistor' is a component in a circuit whereas the 'resistance' is a variable in physics.
- The total resistance in a series circuit is calculated by adding up all the resistances in the circuit. Expressed as a formula: $R_{tot} = R_1 + R_2 + R_3 + ...$
- The total voltage in a series circuit is divided up across the various resistors in the circuit. Expressed as a formula: $U_{tot} = U_1 + U_2 + U_3 + ...$
- The voltage across each resistor is calculated by multiplying its resistance by the current. Expressed as a formula: $U_1 = I \cdot R_1$, $U_2 = I \cdot R_2$, and so forth.
- The overall resistance in a parallel circuit is calculated using the formula: $\frac{1}{R_{tot}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$
- The total current in a parallel circuit is calculated by adding up all the currents in the various branches. Expressed as a formula: $I_{tot} = I_1 + I_2 + I_3 + ...$

CONCEPTS

equivalent resistance
Term for the overall resistance if multiple resistors are connected in series or in parallel.

total current
The current in the unbranched part of a parallel circuit.

5.4 AUTOMATIC CIRCUITS

REMEMBER

- Every automatic circuit consists of a sensor, a switch and an actuator.
- The sensor produces an electrical signal. The switch responds to this signal by switching the actuator on (or off).
- A transistor is in the ON position if a current is flowing from the base to the emitter. In that situation, a current flows from the collector to the emitter.
- The transistor is in the OFF position if no current is flowing from the base to the emitter. In that situation, no current flows from the collector to the emitter either.

CONCEPTS

actuator
Part of a circuit that performs the desired action.

base
One of the three terminals (connections) in a transistor. The size of the current through the base determines whether the collector lets current through.

collector
One of the three terminals (connections) in a transistor. The size of the current flowing through the base determines whether current flows through the collector.

emitter
One of the three terminals (connections) in a transistor.

sensor
Part of a circuit that passes on information about the environment using an electrical signal.

switch
Part of a circuit that switches the current on or off.

transistor
Part of a circuit that functions as an automatic switch.

Go to the *Flash cards* and the *Diagnostic test*.

6 Radiation

MAKING IMAGES USING RADIATION

A variety of imaging techniques are used in hospitals. These create images such as infrared photographs, X-rays and various kinds of scans, all of which give the doctors a picture of the situation inside a body.

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4 Working with gamma radiation 155

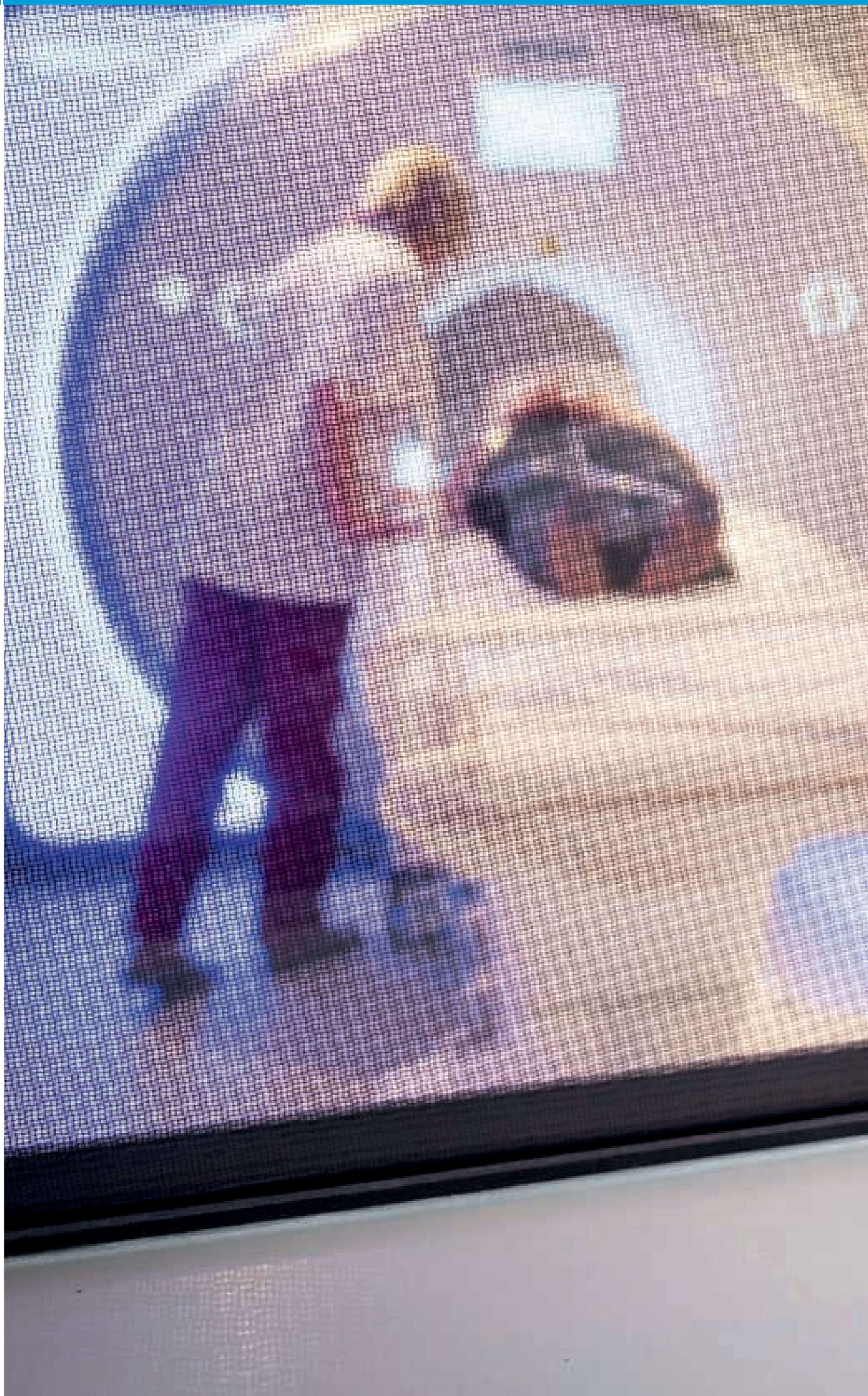
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COMPLETION

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Patient Applications Transfer Edit View Image Tools Scroll Evaluation System Options Help
Waiting for scan instructions.
Stimu=NM SAR=NM

What do you already know about light and radiation?

LEARNING OBJECTIVES

1. You can explain what the frequency of a vibration is.
2. You can explain what a spectrum is and how you can make one visible.
3. You can indicate where infrared and ultraviolet light are located in the electromagnetic spectrum.
4. You can draw rays.

In Parts 1 and 2 of Nova NaSk, you already learned some facts about light and radiation. You will need this knowledge when you start this chapter. If you want to do a quick check of what you can remember, do the following exercises.

EXERCISES TESTING YOUR PRIOR KNOWLEDGE

1 Explain what the frequency of a vibration is.

....

....

2 What is a spectrum?

○ A an artificial, very bright light source
○ B a prism with a triangular cross-section
○ C light that is split up into a sequence of colours

3 Your eyes are only sensitive to visible light. You can't see infrared radiation (IR) or ultraviolet radiation (UV).
Show where IR and UV radiation belong in figure 1.

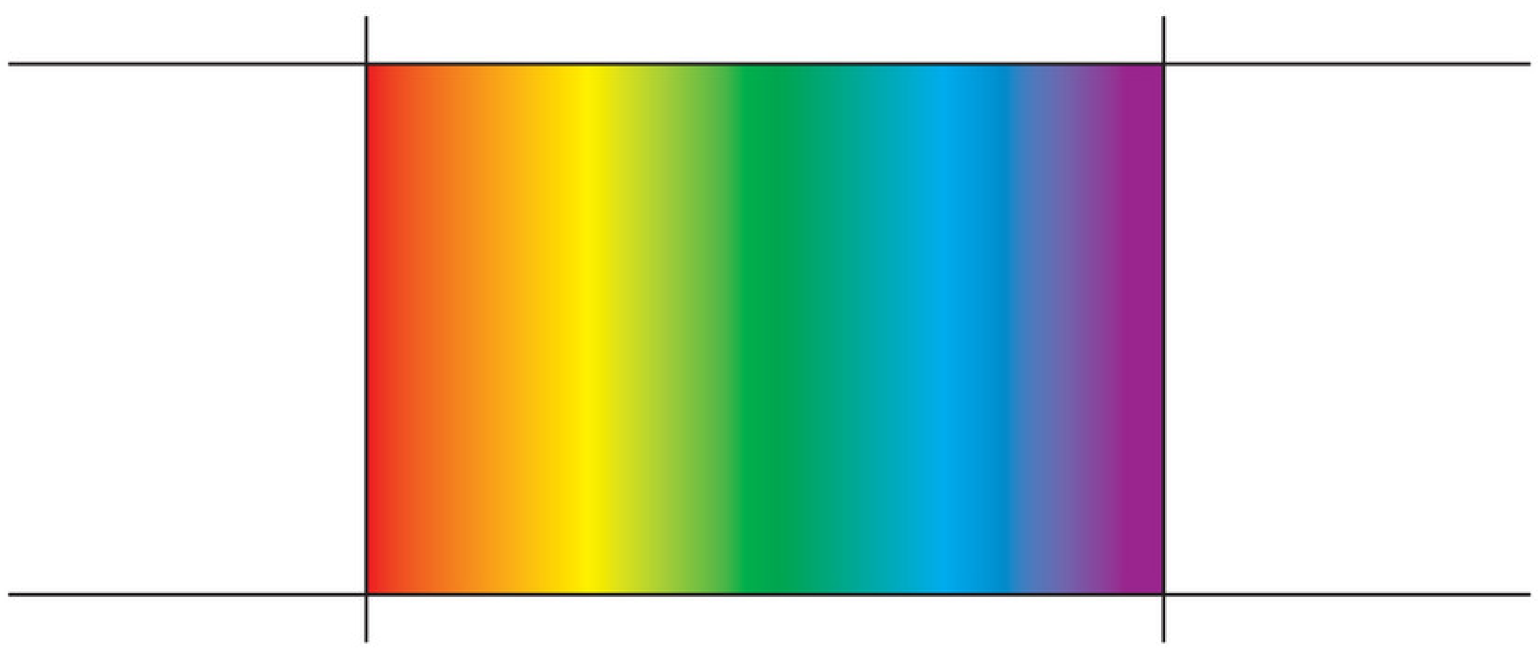


figure 1 Visible light.

4 The LED bulb in figure 2 emits light.
Draw at least ten rays in the figure to show this.



figure 2 A LED light.

If you want to know whether you have enough prior knowledge for this chapter, you can take the online *Prior knowledge test*. You can also find videos about the key learning objectives for this chapter there.

1 Electromagnetic radiation

LEARNING OBJECTIVES

6.1.1 You can describe how a mobile phone transmits and receives information using electromagnetic waves.
6.1.2 You can write down and explain three features of electromagnetic radiation.
6.1.3 You can do calculations using the wavelength, speed of light and frequency.
6.1.4 You can classify the different types of electromagnetic radiation within the electromagnetic spectrum.
6.1.5 You can describe the effects of ionising and non-ionising radiation.
PLUS 6.1.6 You can describe and explain the particle nature of electromagnetic radiation using Planck's formula.

When they hear the word 'radiation', a lot of people think of nuclear energy or radioactivity. But there are many other types of radiation. Your phone is also a radiation source, as is a microwave oven or a remote control. Even your body is a radiation source: it is continually emitting infrared radiation.

TRANSMITTING AND RECEIVING

You can only use your mobile if you have 'coverage'. There has to be a transmitter mast in the neighbourhood that your phone can communicate with. Information is then continuously exchanged between the antenna of your phone and the antenna on the transmitter mast.

When your phone is transmitting, an alternating current goes through the antenna (figure 1). The electrons in the antenna move up and down at a high frequency. That motion creates **electromagnetic waves** that move away from the antenna at a very high speed.



figure 1 Transmitting using your telephone.

When the electromagnetic waves reach the mast, the electrons there start to move too: the electrons in the mast's antenna move up and down at the same rate as the electrons in the phone antenna. This creates an alternating current of the same frequency as the alternating current in the phone antenna. This allows signals to be passed from the phone to the mast.

WAVELENGTH AND FREQUENCY

Just like water waves, electromagnetic waves move away from the source. Figure 2 shows you how this works for water waves. The 'source' is an object that goes up and down and makes the water move. The 'receiver' is a wooden block that starts moving up and down when the waves reach the block.

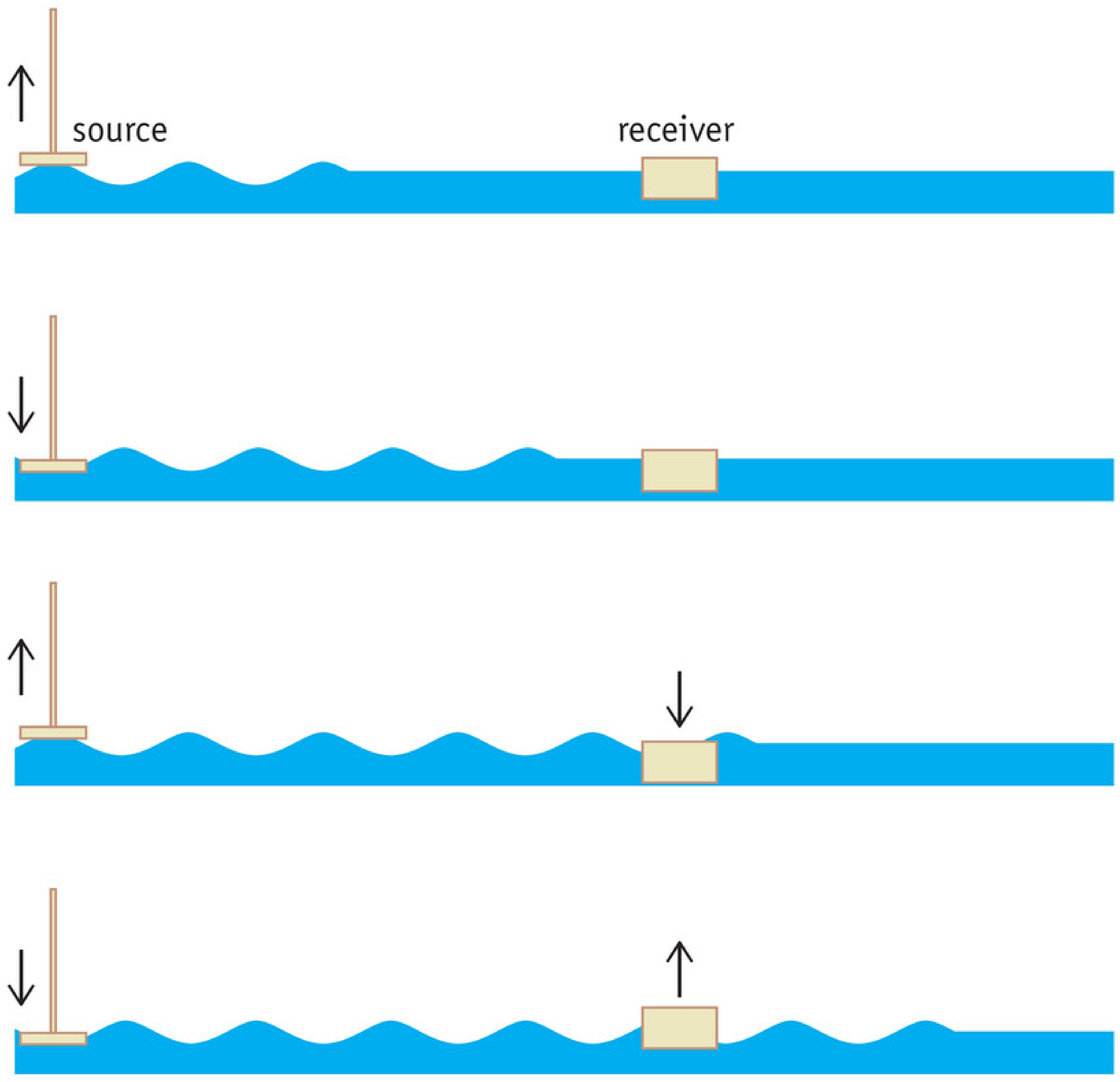


figure 2 Waves propagate from the source to the receiver.

As well as the similarities, there are also major differences:

- Electromagnetic waves do not move in just one plane like water waves, but in all directions.
- Electromagnetic waves are not vibrations in a substance such as water or air, but they propagate independently – even through a vacuum.
- Electromagnetic waves always have the same speed in a vacuum: 299,792,458 m/s, which rounds off to $3.0 \cdot 10^8$ m/s. This speed is called the **speed of light** and it has its own symbol, *c*.

The number of wave peaks that pass in a second is called the **frequency** of the wave. The distance between two successive wave peaks (or wave troughs) is called the **wavelength** (figure 3). The symbol used for this is λ, the Greek letter lambda. You can calculate the wavelength by dividing the speed of the wave (the distance covered per second) by the frequency (the number of waves per second). This is how you find the distance for each wave, which is the wavelength. Expressed as a formula:

$$\lambda = \frac{c}{f}$$

where:

- λ is the wavelength in metres (m);
- c is the speed of light in metres per second (m/s);
- f is the frequency in hertz (Hz).

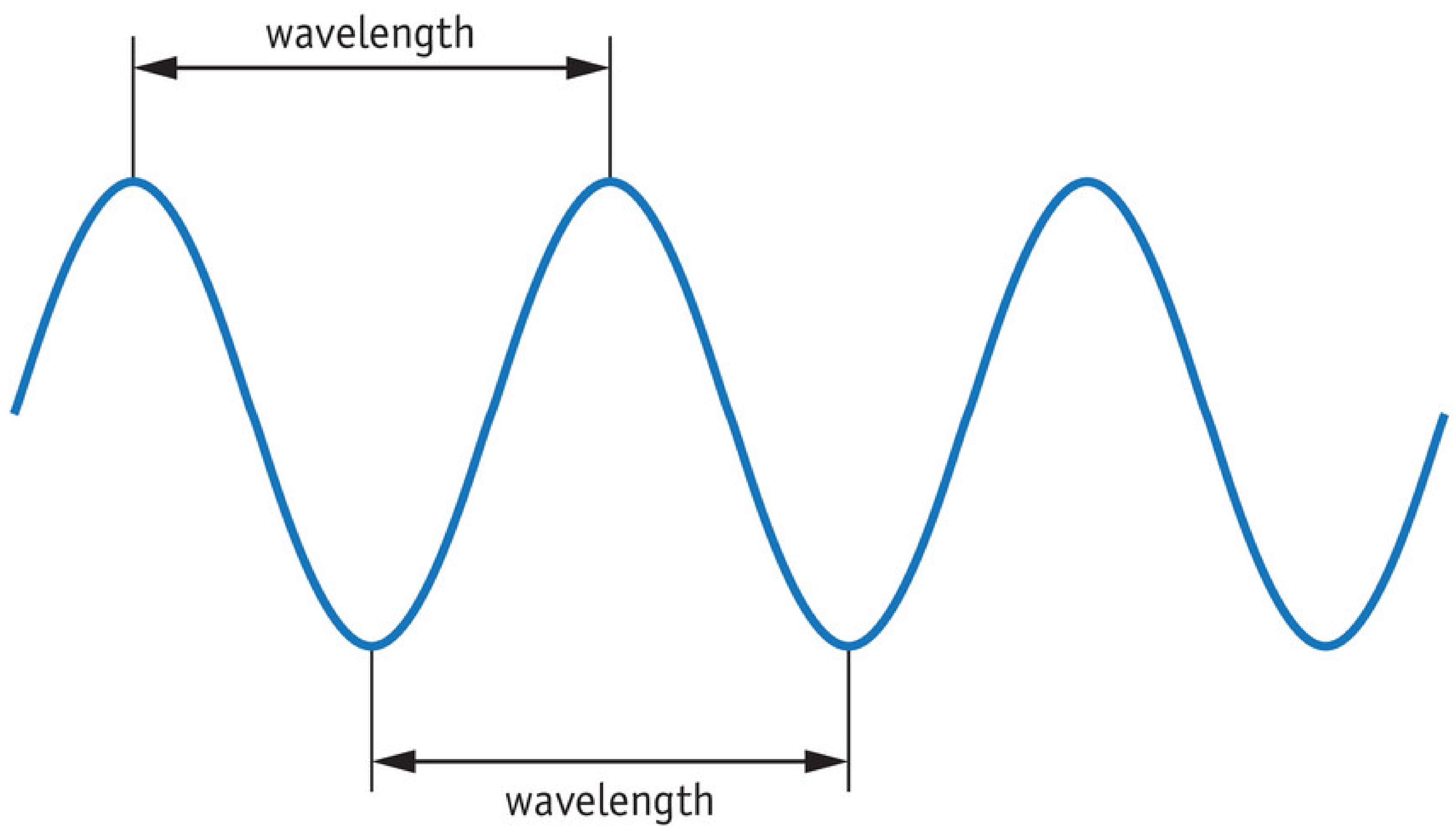


figure 3 This is how you can calculate the wavelength λ.

Every frequency therefore has a specific wavelength (in a vacuum). Mobile phones use waves with a frequency of 800 to 1800 MHz. That corresponds to wavelengths of 16 to 38 cm. Light is also an electromagnetic wave phenomenon but at much shorter wavelengths. These shorter wavelengths are usually given in nanometres. A nanometre is a billionth of a metre (1 nm = 10^{-9} m).

EXAMPLE EXERCISE 1

A laser radiates blue light with a wavelength of 470 nm.
Calculate the frequency of this blue light.

given $c = 3.0 \cdot 10^8$ m/s
$\lambda = 470$ nm $= 470 \cdot 10^{-9}$ m

required $f = ?$

working $f = \frac{c}{\lambda} = \frac{3.0 \cdot 10^8}{470 \cdot 10^{-9}} = 6.4 \cdot 10^{14}$ Hz

THE ELECTROMAGNETIC SPECTRUM

The theory of electromagnetic waves lets you describe a wide range of radiation types. This theory applies not only to radio waves and light but also to infrared radiation (IR radiation), ultraviolet radiation (UV radiation), X-rays and gamma radiation.

Figure 4 shows the types of electromagnetic radiation ordered by wavelength. This results in an electromagnetic **spectrum** ranging from radio waves to gamma rays. The spectrum of visible light is only a small fraction of this, a band from 780 nm (deep red) to 380 nm (far violet).

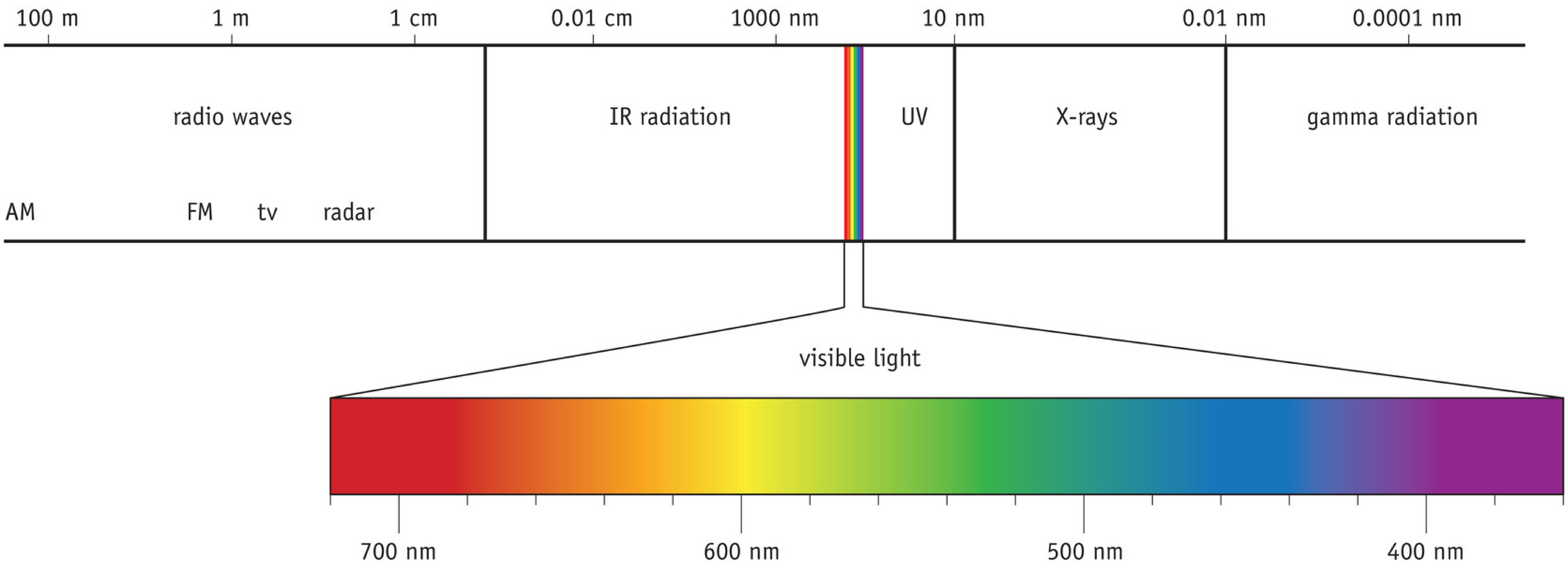


figure 4 The electromagnetic spectrum: from radio waves to gamma rays.

The properties of electromagnetic radiation depend on the wavelength. You can see this in the spectrum of light (figure 4). Every spectral colour has its own wavelength (in a vacuum). Red light has the longest wavelength and violet light the shortest. If you know the wavelength, you also know what colour the light is.

Light is the only kind of electromagnetic radiation that you can see. Your eyes are sensitive to the colours of 'normal' light: from red to violet. All other forms of radiation are invisible to human eyes. To make them visible, you need special instruments such as an infrared camera (figure 5).



figure 5 An infrared camera making a false-colour image of a radiator. Red represents a lot of IR radiation (where it is hot) and blue is for not much IR radiation (where it is cooler).

EFFECTS OF RADIATION

When radiation is absorbed, the energy in the radiation will be released. You will notice this if you sit in bright sunlight wearing a black T-shirt: you will soon get hot because of the radiation (infrared and light) that falls on your T-shirt. The temperature of your skin rises, because the radiant energy is converted into heat. A relatively large amount of energy is needed for this.

Some types of radiation have another effect too: their radiation energy can break substances down. You will notice this if you leave a sheet of coloured paper in the sunlight for several days, for example. The ultraviolet radiation in the sunlight breaks down the dye molecules. That makes the colours fade (figure 6). Ultraviolet radiation (UV) can also damage the DNA (the genetic material) in your skin cells.

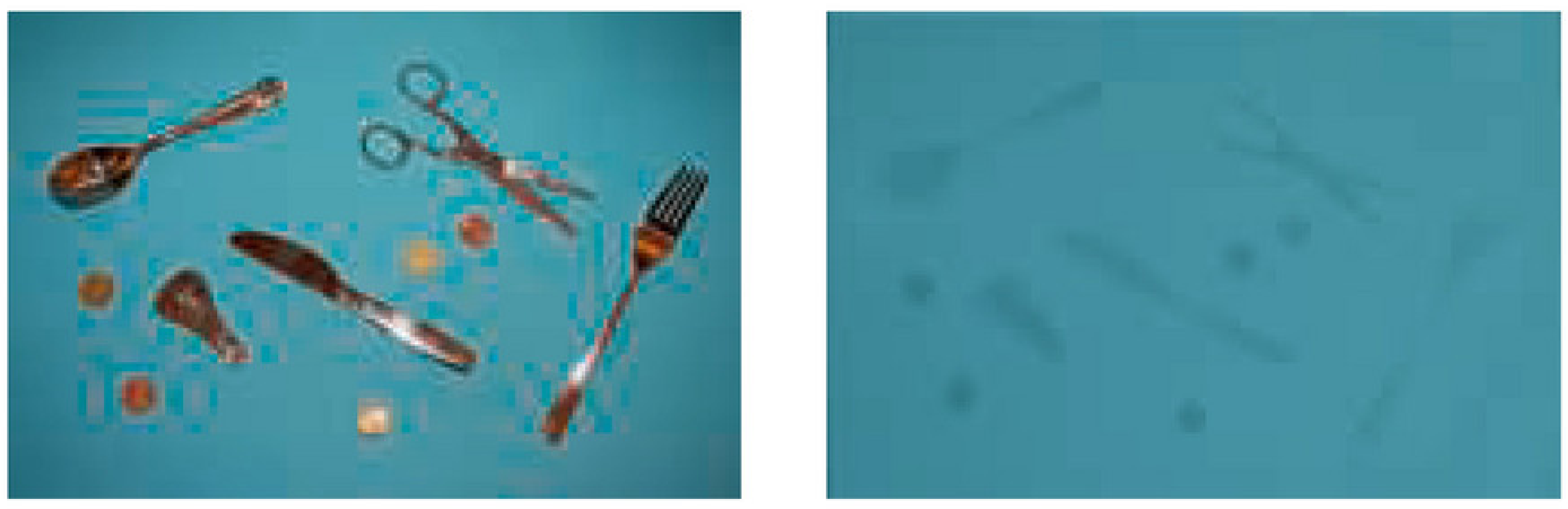


figure 6 An experiment with UV radiation: the paper has visibly discoloured after two weeks in the sun.

Radiation that can break molecules down is called **ionising radiation**. Radio waves, infrared (IR) and light are not ionising. UV is slightly ionising, and X-rays and gamma radiation are highly ionising. As a result, even very small amounts of X-rays or gamma radiation can harm your health. That is why you must be very careful with these forms of radiation.

PLUS PHOTONS

Figure 7 shows you a light sail (or solar sail), a spaceship that moves because of solar radiation 'colliding' with the sail. A number of light sails like these have already been launched. It is not actually so obvious that the solar sail will move when light falls on it, because light does not have any mass. When a lightweight ping-pong ball collides with a stationary snooker ball, the effect is tiny. So if something with no mass at all collides with the snooker ball, you would expect nothing whatsoever to happen.

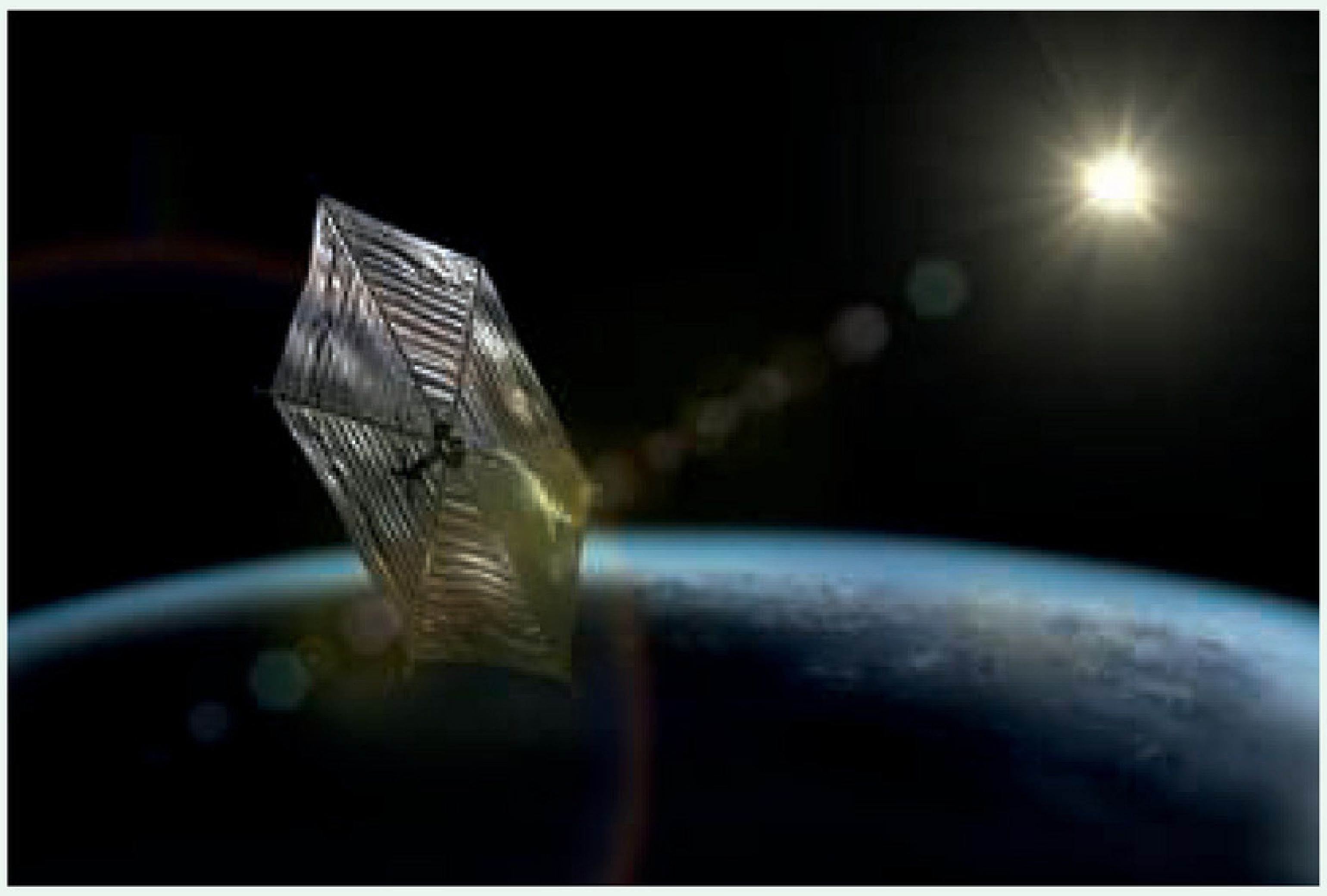


figure 7 A light sail is propelled through space by sunlight.

The propulsion of a light sail can only be explained using quantum theory. Around 1900, the German physicist Max Planck proposed that electromagnetic radiation should be seen as a type of particle or 'energy packet'. The name given to this was the **photon** (from the Greek *phōs* = light). The force exerted by colliding photons depends (in this theory) only on the energy of the photons. The energy of a photon is in turn determined by its frequency:

$$E = h \cdot f$$

where:
- E is the energy of the photon in joules (J);
- h is a constant (Planck's constant) in joule-seconds (Js);
- f is the frequency in hertz (Hz).

Physicists now know that light has properties of both particles and waves. The 'particle nature' is best seen with gamma radiation. A gamma photon has a high frequency and therefore a lot of energy, making it capable of breaking up the DNA molecules in your body when it 'collides' with them (figure 8).

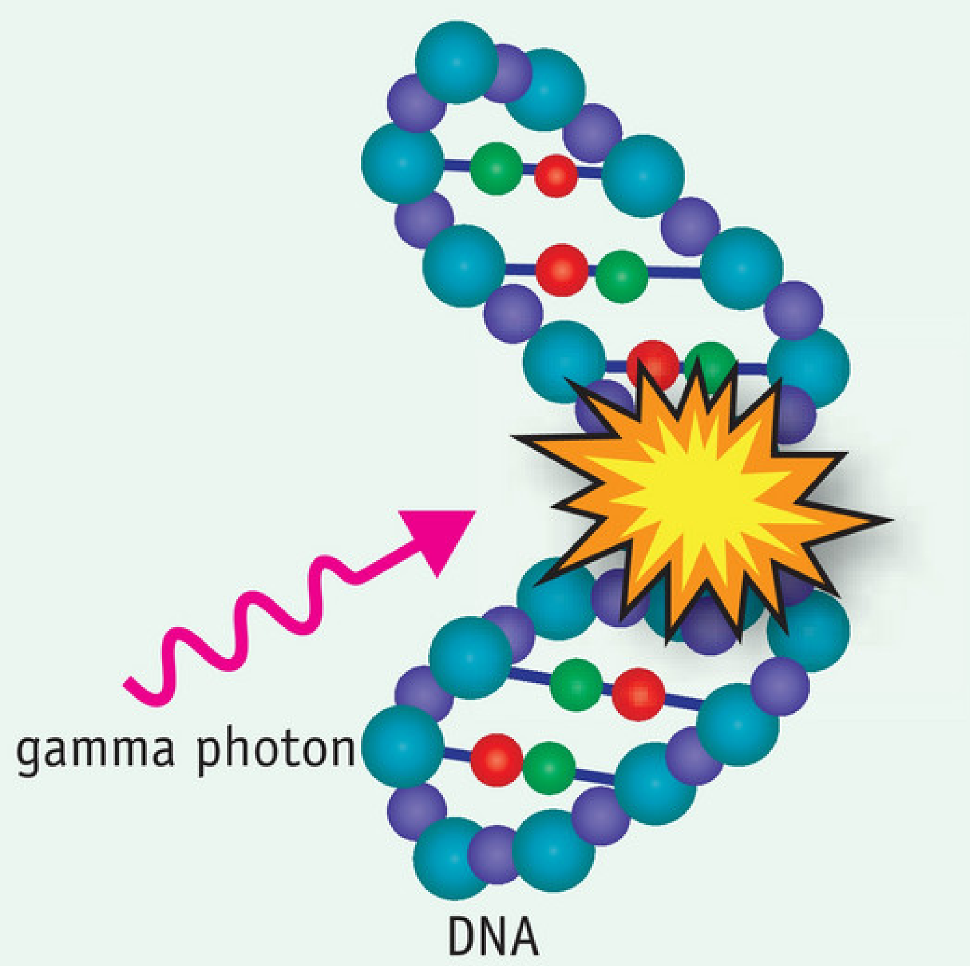


figure 8 A gamma photon can damage a DNA molecule.

Table 1 lists the typical energies of various types of radiation. The greater the energy, the more you will notice the particle nature of the radiation and the more hazardous that radiation is.

table 1 Various types of radiation and the order or magnitude of the energy of the photons.

frequency (Hz)	energy (J)
radio waves	10^{-23}
mild	10^{-19}
X-ray	10^{-16}
gamma	10^{-14}

Practice the concepts using the *Flash cards*.

COURSE MATERIAL

1

Answer the following questions.

a What is the speed of electromagnetic waves in a vacuum?

b What types of radiation have longer wavelengths than light?

- ☐ A radio waves
- ☐ B infrared radiation
- ☐ C ultraviolet radiation
- ☐ D X-rays

c What type of radiation has wavelengths of between 10 nm and 0.01 nm?

- ○ A radio waves
- ○ B infrared radiation
- ○ C ultraviolet radiation
- ○ D X-rays

d What type of electromagnetic radiation has a slightly ionising effect?

- ○ A radio waves
- ○ B infrared radiation
- ○ C ultraviolet radiation
- ○ D X-rays

2

You learned a formula in this section that gives the relationship between the frequency, the wavelength and the speed of an electromagnetic wave.
Write that formula down:

a in the form that you would use to calculate the frequency;

b in the form that you would use to calculate the wavelength.

IN PRACTICE

3

You can find all kinds of radiation sources in the world around you.
Complete the missing data in table 2.

table 2 Five radiation sources.

examples of radiation sources	type of radiation
	radio waves
central heating radiator	
	visible light
	ultraviolet
X-ray camera	

4 Beth creates a wave motion in a skipping rope by moving one end of it up and down. She has attached the other end of it to a wall.
Use the data in figure 9 to calculate:

a the frequency.
b the wavelength. Note the scale shown.
c the speed of the wave.

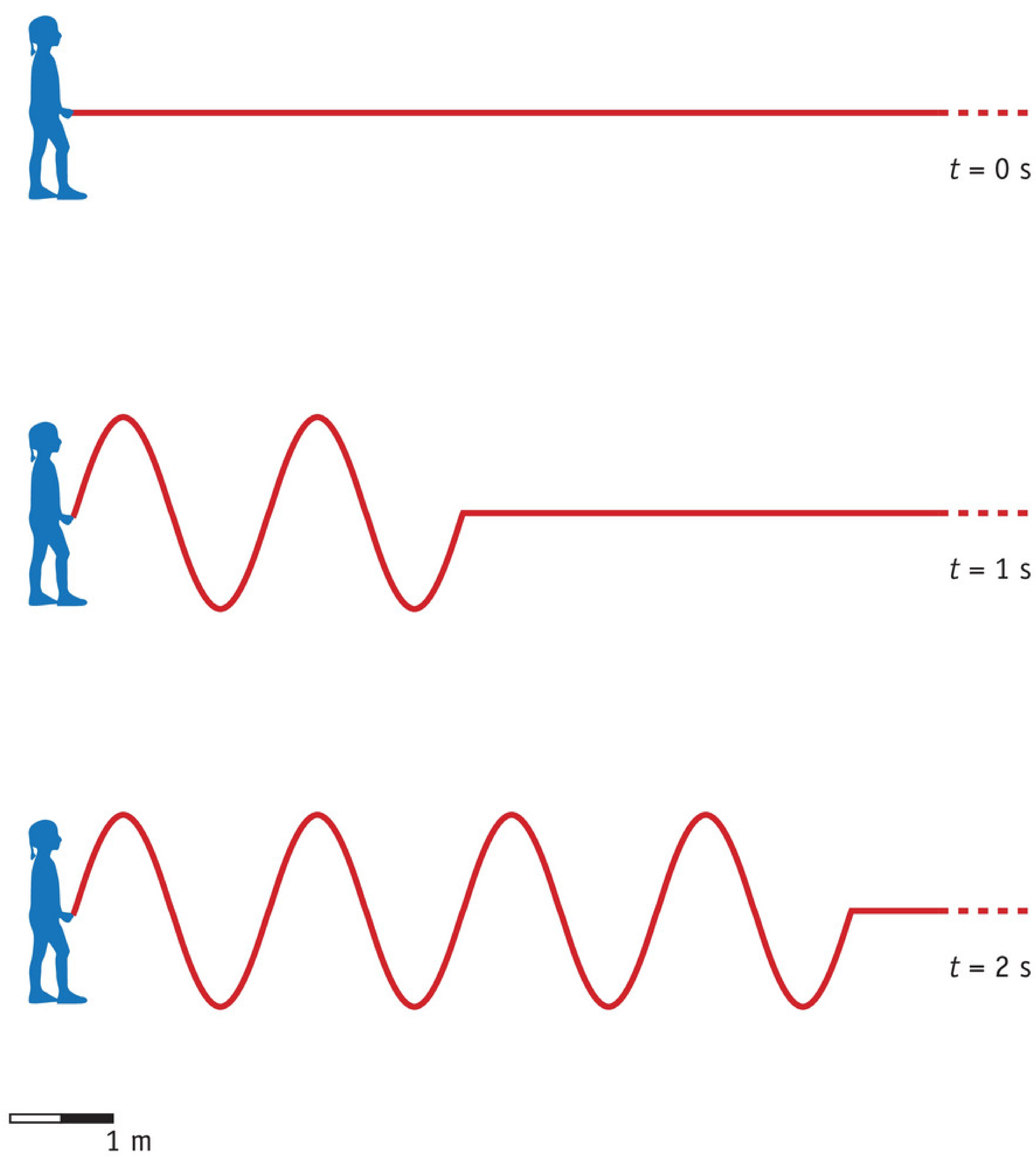


figure 9 A wave in a rope.

5 It takes a radio signal between 3 and 21 minutes to cover the distance between the planet Mars and the Earth.

a Explain why the time needed can vary so much.
b On 6 August 2012, the Mars rover *Curiosity* landed on the planet. The signal from *Curiosity* only reached Earth after 13 minutes and 48 seconds.
Calculate the distance between Mars and the Earth at that moment. Give the answer in millions of kilometres.

★ 6 Miriam is reading the website of Radio Rijnmond: “Our transmissions have been on 93.4 MHz since 1 July.”

a Calculate the wavelength of the radio waves.
b Explain whether Radio Rijnmond is an AM or FM broadcaster.
c Radio broadcasting distinguishes between long-wave, medium-wave and short-wave transmissions.
Determine using figure 4 which type of wave Radio Rijnmond uses for its broadcasts.

7 Look at the infrared photo in figure 10.

a Which parts of the dog's body are at the highest temperature?

b The temperature of these body parts is roughly .... °C.

c Which part of the body has the lowest temperature?

d Explain why an infrared camera often gives clearer images at night than in the daytime.



figure 10 A dog in infrared.

8 The radiation emitted by a laser has a single fixed wavelength. Table 3 shows six types of lasers and their wavelengths. Figure 4 lists the properties and wavelengths of the types of radiation.

a Write down the type of radiation for each laser in table 3.

b Write down the colours of the light in table 3 for the lasers that emit visible light.

table 3 Six types of laser.

type of laser	wavelength (nm)	type of radiation	colour
argon	1090		
helium-cadmium	442		
copper	511		
krypton fluoride	248		
ruby	694		
nitrogen	337		

★ 9 You can see from the wavelength what type of radiation you are dealing with.

a Write down the right type of radiation for a wavelength of:

A	10 cm	○	○	1	green light
B	0.01 cm	○	○	2	IR radiation
C	520 nm	○	○	3	radio waves
D	1 nm	○	○	4	X-rays

b Calculate the frequency of the radiation with a wavelength of 10 cm.

10 Figure 11 contains part of a report by the fire brigade. It is describing the risks of an accident with a tanker containing LPG (*liquid petroleum gas*).

a Explain why the tank could rupture if it is “irradiated by a fire”.

b The text refers to ‘radiant heat’. What type of radiation is it talking about?

c Why is this type of radiation hazardous or even deadly in large amounts?

d Why does the risk depend on the distance to the radiation source?

LPG explosion

In the worst case, the tanker will be irradiated by the fire after which the wall of the tank gives way, the flammable liquid ignites and a large fireball is created that emits radiant heat. This is known as a *bleve*, a *boiling liquid expanding vapour explosion*. The intense radiant heat will immediately cause casualties up to a distance of as much as 230 metres, and there can be fatalities and injuries up to 600 metres away as a result of burns.



figure 11 The risks of an LPG explosion.

Test what you know with *Test yourself*.

PLUS PHOTONS

11 Answer the following questions.

- **a** What is a photon, according to Max Planck's theory?
- **b** A sodium lamp for street lighting emits light with a wavelength of 589 nm. Calculate the frequency.
- **c** Calculate the energy of a photon emitted by the sodium lamp. Use Planck's constant for this: $6.626 \cdot 10^{-34}$ Js.
- **d** The sodium lamp emits $4.44 \cdot 10^{19}$ photons every second. Work out the power rating of the sodium lamp.
- **e** If your body absorbs just a dozen joules or so of radiant energy as gamma photons, it can be deadly.
  Judith says, "If I stay for long enough under the sodium lamp, then there'll be a point when I've absorbed just as much energy, so standing under the sodium lamp for a long time must be dangerous." Where has Judith's thinking gone wrong?

12 A photon hitting the light sail in figure 7 is reflected back in the direction it came from. The sail will move slightly more quickly after the collision because the photon has transferred energy to the sail. This changes the wavelength of the photon a little.

- **a** Explain whether the wavelength of the photon is a little longer or a little shorter after the collision.
- **b** At a given moment, the power of the radiation hitting the solar sail is $1.3 \cdot 10^{3}$ W per square metre. The surface area of the light sail is 750 m^2. The incident photons have an average energy of $3.5 \cdot 10^{-19}$ J.
  Calculate the number of photons hitting the light sail every second.

2 Light and lenses

LEARNING OBJECTIVES

6.2.1 You can describe how a positive lens refracts a parallel beam of light.
6.2.2 You can explain the difference between a focused photo and a blurry one.
6.2.3 You can show the object distance and the image distance in a drawing.
6.2.4 You can describe the paths of the two construction rays before and after the lens.
6.2.5 You can use the two construction rays to determine where the image will be located.
PLUS 6.2.6 You can explain the refraction of light using Snell's Law and demonstrate it with calculations.

Lenses are found in all kinds of devices: cameras, binoculars, projectors and telephones. The glasses in spectacles are lenses too, as are contact lenses and the 'natural' lenses in your eyes. Lenses let you see the world around you clearly and record images of that world in photos and videos.

REFRACTION BY LENSES

EXP. 1

Light moves in straight lines. But if light meets a piece of glass or another transparent material at an angle, its direction changes. This effect is called **refraction**. This effect is seen in a magnifying glass when used as a lens that concentrates a beam of sunlight into a burning point.

Figure 1 shows you how a magnifying glass refracts light. The lens that is used is thicker in the middle than at the edges. This shape is called a **convex** or **positive lens**. Before the sun's rays fall onto the lens, they are parallel to the **main axis** of the lens (that is the line that runs through the centre of the lens perpendicular to the lens). After passing the lens, the rays converge and all meet at one point: the **focal point**.

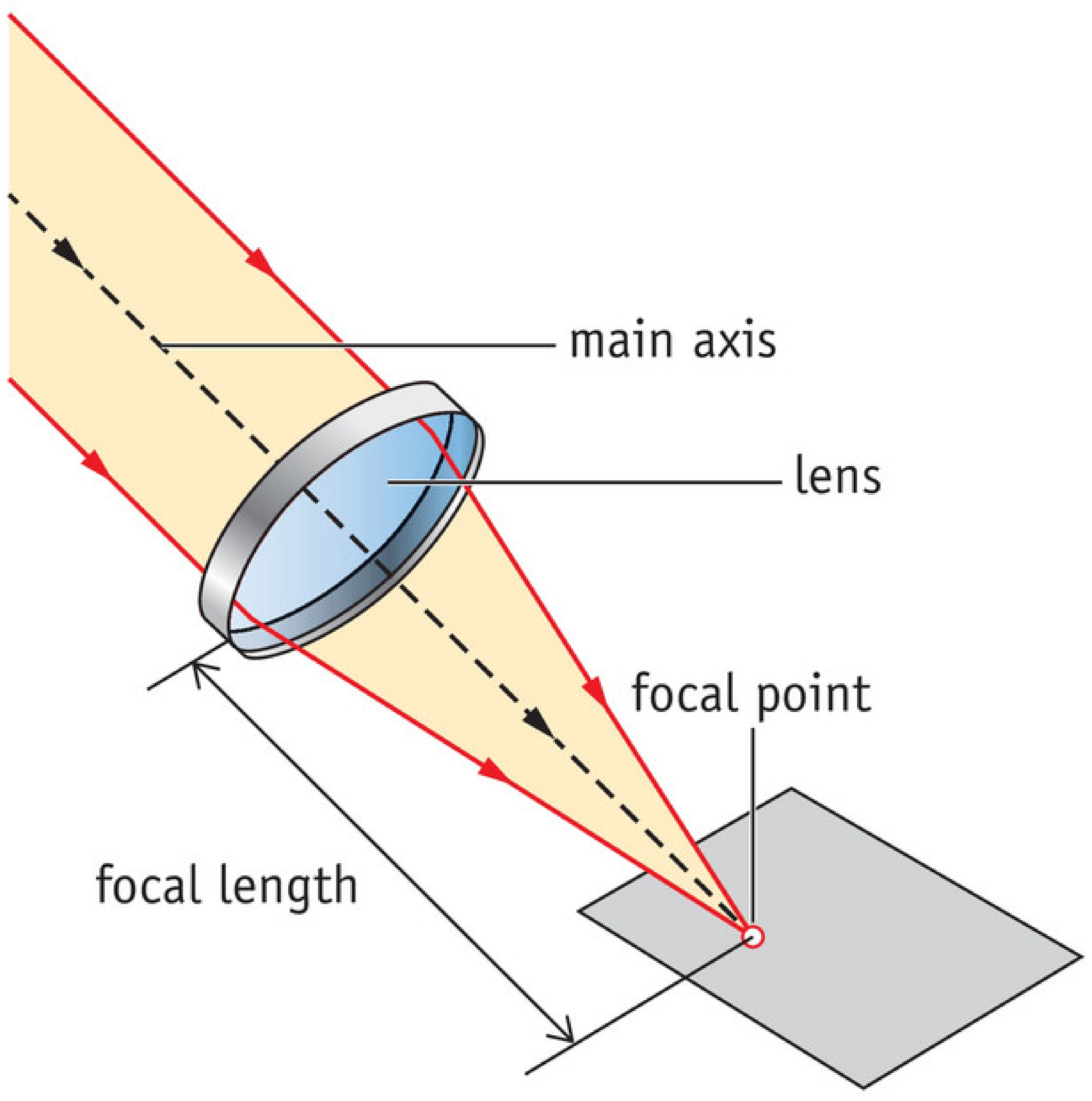


figure 1 How to use a magnifying glass to focus a burning spot.

In drawings, the focal point is indicated by the letter F. The distance from the centre of the lens to the focal point F is called the **focal length**, f. The focal length is an important property of a lens. The shorter the focal length, the more strongly the lens refracts the light.

CREATING IMAGES USING A LENS

EXP. 2+3

You can use a positive lens to create an image of an object on a screen. You do this when you take a photograph, for example. A lens in the camera produces a small image of the view in front of the lens on a light-sensitive image sensor chip. A computer in the camera records that image pixel by pixel in a file. The file is then stored in the memory. This lets you view, upload or print the image later on.

When you take a photograph, light from the object falls on the lens. This will generally be reflected light but can sometimes be light emitted by the object itself, such as a bulb. The lens makes sure that all the light from any one point on the object comes together at a single point again. This point is called the **image point** I of the object point P. A single photo consists of millions of such image points or 'pixels'.

If the image sensor is at the right distance from the lens, the photo will be sharp. A photo consists of pixels that do not overlap each other. If the sensor chip is not at the correct distance, the photo will be blurred. The image points in the photo have then become small circles that overlap each other partially (over several pixels), making the boundaries between the coloured fields become vague. If you focus on an object in the foreground, the background will not be shown clearly (figure 2).



figure 2 The foreground is in sharp focus but the background is blurred.

OBJECT DISTANCE AND IMAGE DISTANCE

To adjust the focus of a camera, you have to get two distances matched up:

1 the distance between the lens and the object, this is the **object distance** *o*.

2 the distance between the lens and the sharp image, this is the **image distance** *i*.

The setup shown in figure 3 lets you investigate how focusing works. Slide the screen slowly away from the lens until an absolutely sharp image can be seen on the screen. You will then see that there is just one image distance for every object distance. That is the only distance at which the image is absolutely sharp.

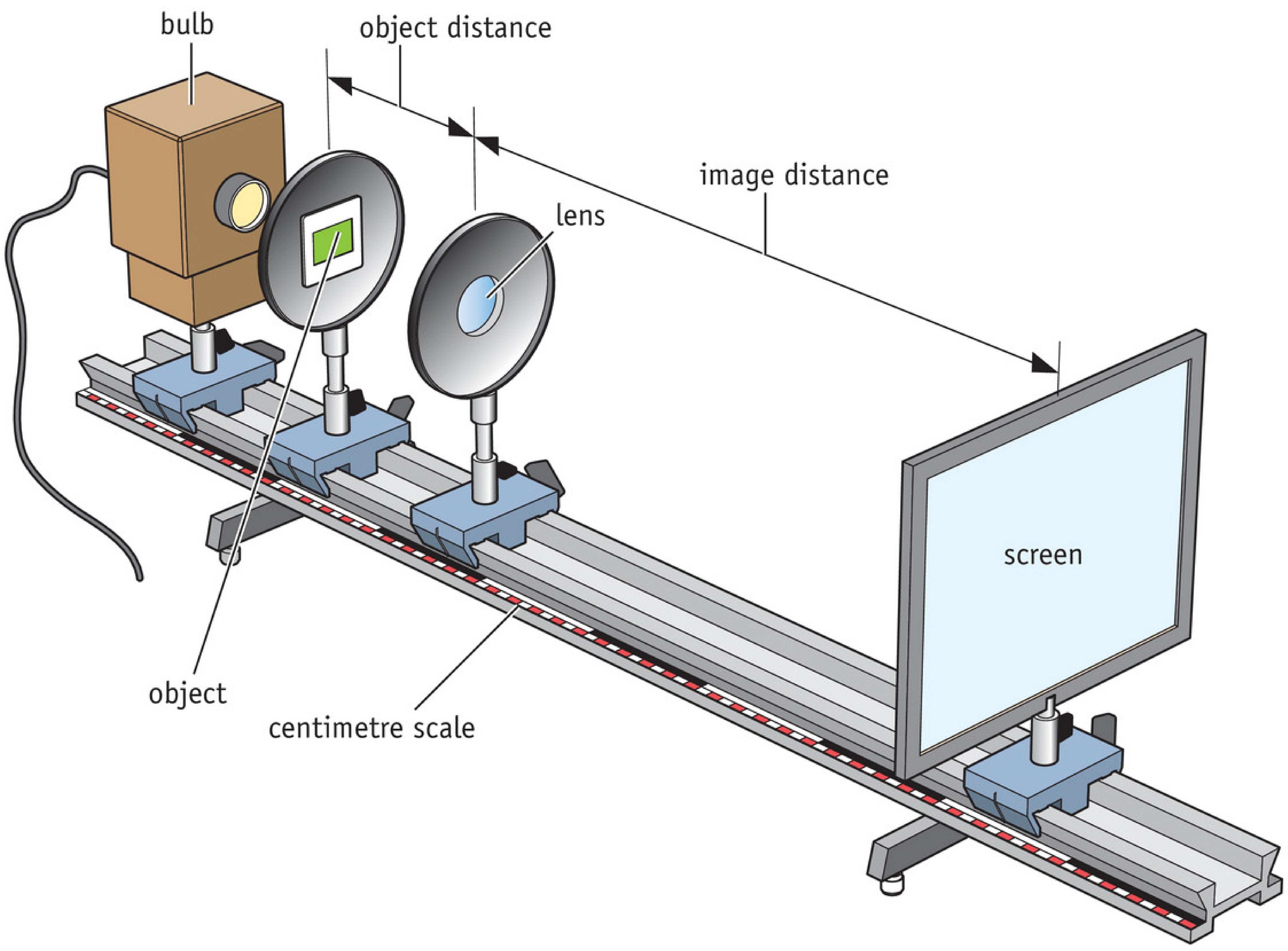


figure 3 This lets you find the object distance for any given image distance.

CONSTRUCTING THE IMAGE

You can also determine the image distance using a scale drawing. This is called **constructing** the image. Two special rays are used for this. You know beforehand exactly how these **construction rays** will travel:

- Construction ray 1 goes through the centre of the lens and does not change direction.
- Construction ray 2 runs parallel to the main axis between the object and the lens. Beyond the lens, this ray will go through the focal point F of the lens.

Figure 4 is a sketch showing how the image of an object can be constructed.

1 Draw the lens and the main axis. Draw the focal point at the right distance from the lens and put a letter F next to it.

2 Draw the object as an arrow O_1O_2 at the right distance in front of the lens. O_2 is on the main axis and O_1 is above it.

3 Draw the two construction rays from O_1. Draw the image point I_1 where the construction rays come together.

4 Draw the image as an arrow I_1I_2. I_2 is on the main axis and I_1 is below it. The image is therefore upside down compared to the object.

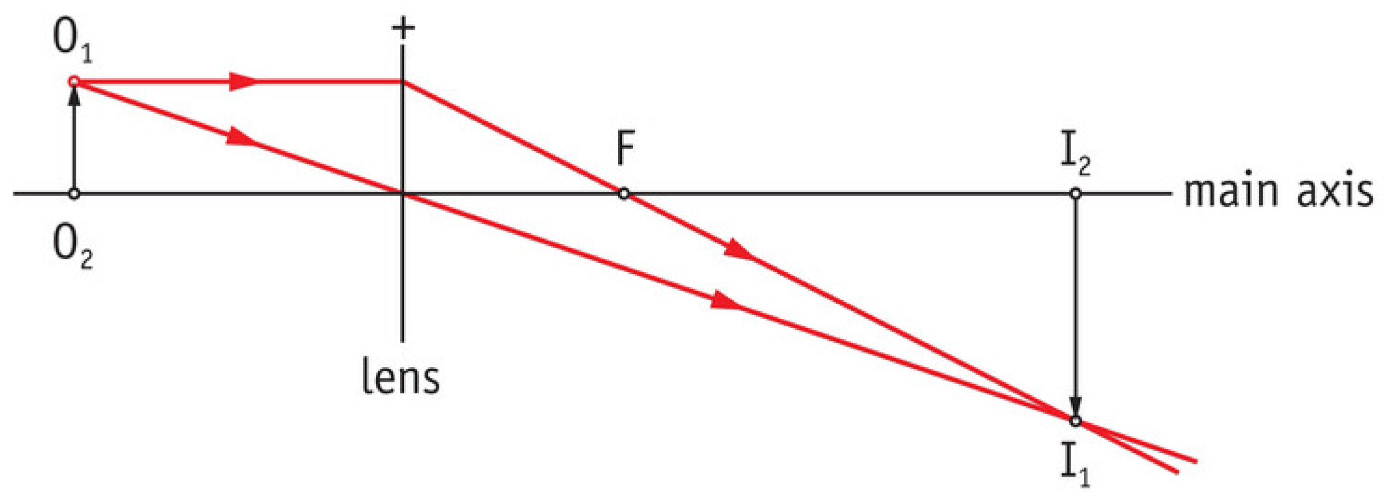


figure 4 How to draw the location of the image.

The object is sometimes bigger than the lens. In that case, you need a trick for constructing the image. You extend the lens in the drawing until it is a little bit bigger than the object. After that, you can use the construction rays again to find the location of the image.

You generally only draw the two construction rays. But once you have found the image point, you can also draw in the paths of other rays. *All* rays that fall on the lens from O_1 will be refracted towards the point I_1 (figure 5). As a result, you see a sharp image point corresponding to O_1 when you put the screen at that spot rather than a small circle of light.

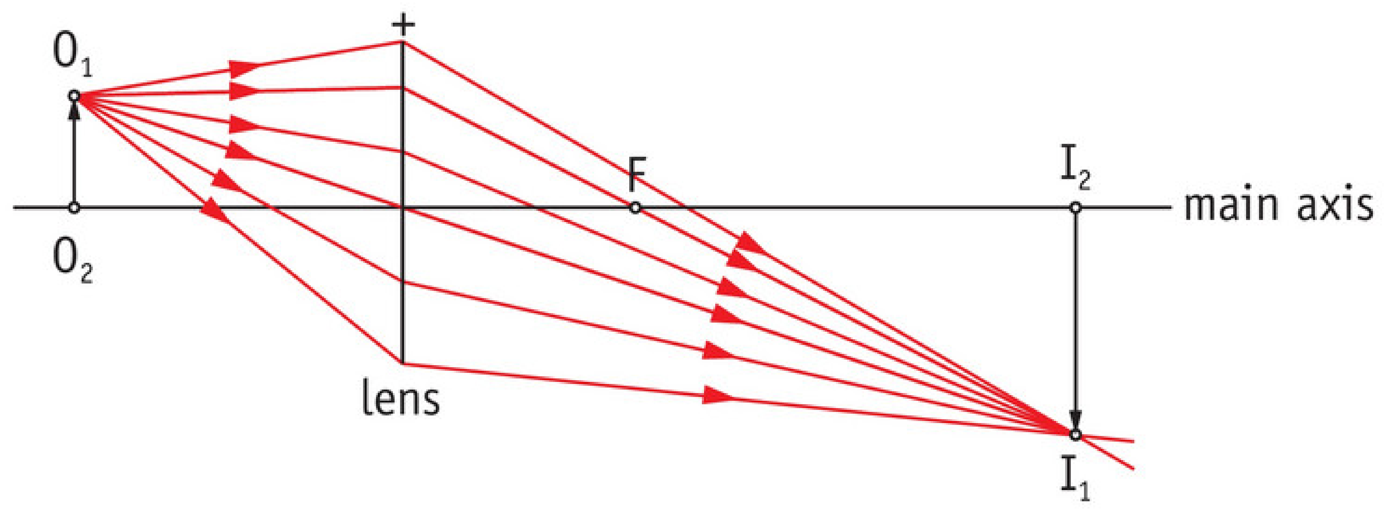


figure 5 This is how you can draw in the paths of the other rays.

PLUS REFRACTION IN LENSES

In figure 6, you can see on the left how a lens changes the direction of a ray of light at the boundary between the air and the glass. This effect is called refraction. The dotted line perpendicular to the surface is called the **normal**. The angle between the incoming ray and the normal is the **angle of incidence** ($\angle i$). The angle between the outgoing ray and the normal is the **angle of refraction** ($\angle r$).

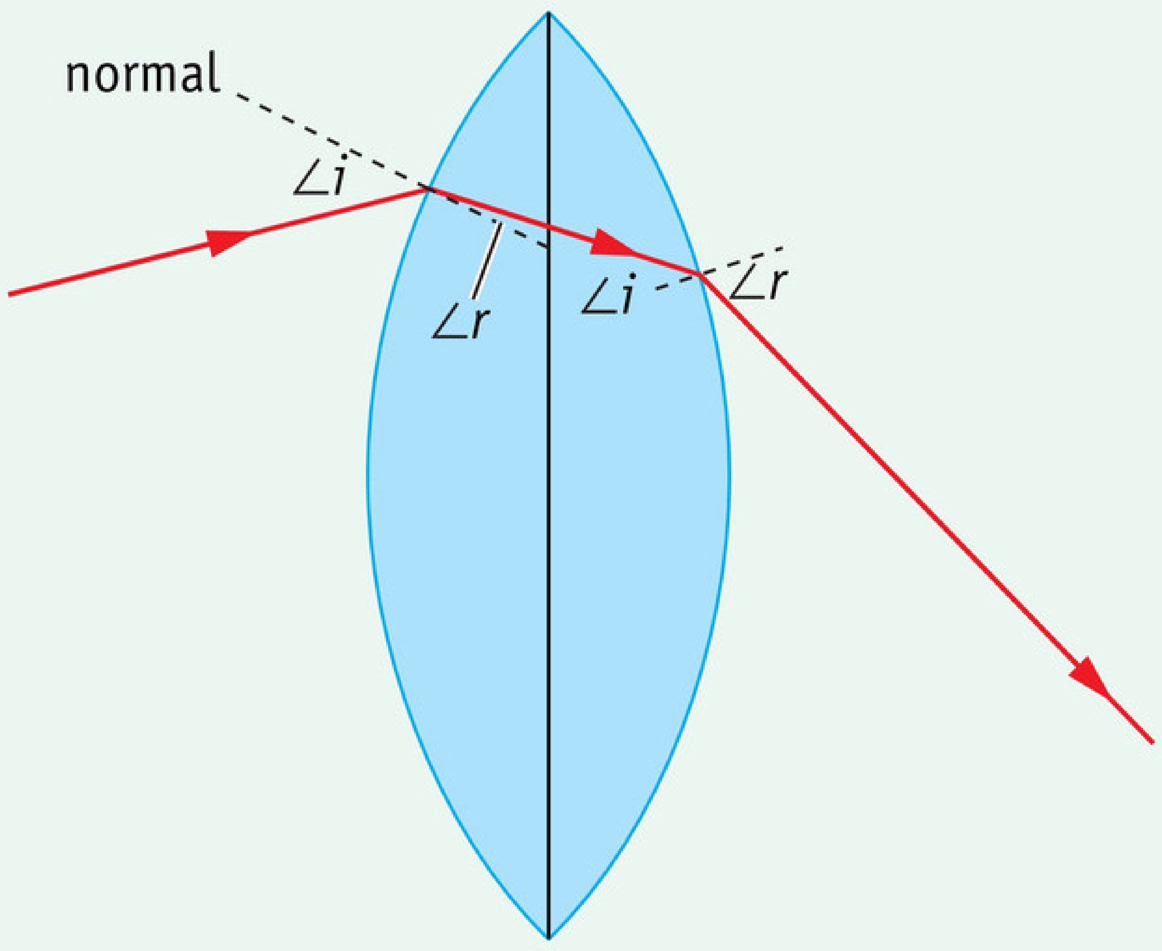


figure 6 Refraction through a lens.

In the sixteenth century, a Dutchman called Willebrord Snell discovered a relationship between $\angle i$ and $\angle r$. This relationship is therefore known as **Snell's Law of Refraction**:

$$\frac{\sin i}{\sin r} = n$$

where:

- i is the angle of incidence in degrees;
- r is the angle of refraction in degrees;
- n is a constant, the **refractive index** (a property of the substance).

This law applies to the refraction of a ray going from air into a substance. Every transparent substance has its own refractive index (table 1). The greater the refractive index, the more strongly the ray is refracted towards the normal in the substance.

table 1 The refractive indices of various substances.

substance	refractive index *n*
alcohol	1.4
diamond	2.4
glass	1.5
ice	1.3
Perspex	1.5
water	1.3

EXAMPLE EXERCISE 1

A light ray coming from air meets a piece of glass at an angle of 40° (figure 7). Calculate the angle of refraction.

given $\angle i = 40°$

$n = 1.5$ (table 1)

required $\angle r = ?$

working The law of refraction means that:

$$\frac{\sin 40^\circ}{\sin r} = 1{,}5$$

$$\sin 40° = 1.5 \cdot \sin r$$

$$\sin r = \frac{\sin 40}{1.5} = \frac{0.643}{1.5} = 0.428$$

The inverse sine (arcsine) button on your calculator tells you that $\angle r = 25°$.

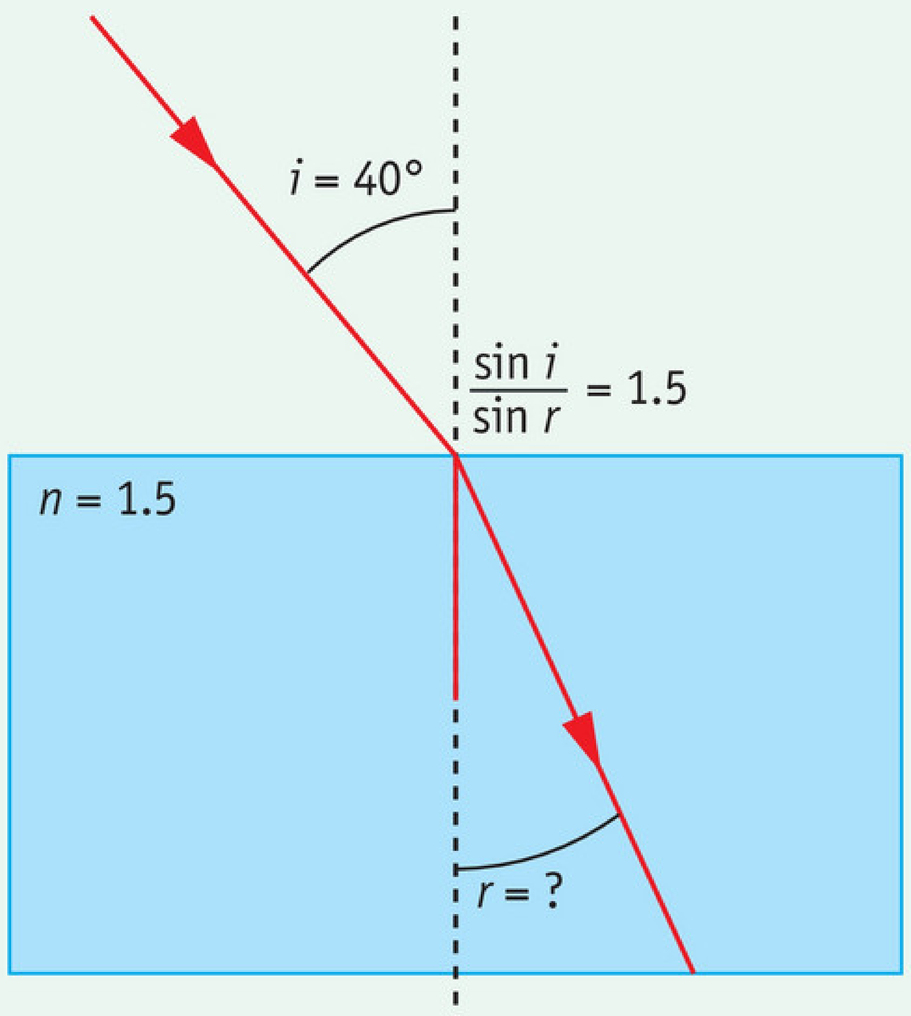


figure 7 Snell's law of refraction lets you work out what the path of the ray will be.

Practice the concepts using the *Flash cards*.

COURSE MATERIAL

1 Answer the following questions.

a How can you tell whether a lens is positive or not?
b How is a parallel beam of sunlight refracted by a positive lens?
c What does the lens in your camera do with the light that comes from any single point of the object?
d What has gone wrong when you take a photo but get a blurred image?

2 Joyce lets sunlight pass through a spectacle lens onto a sheet of paper.

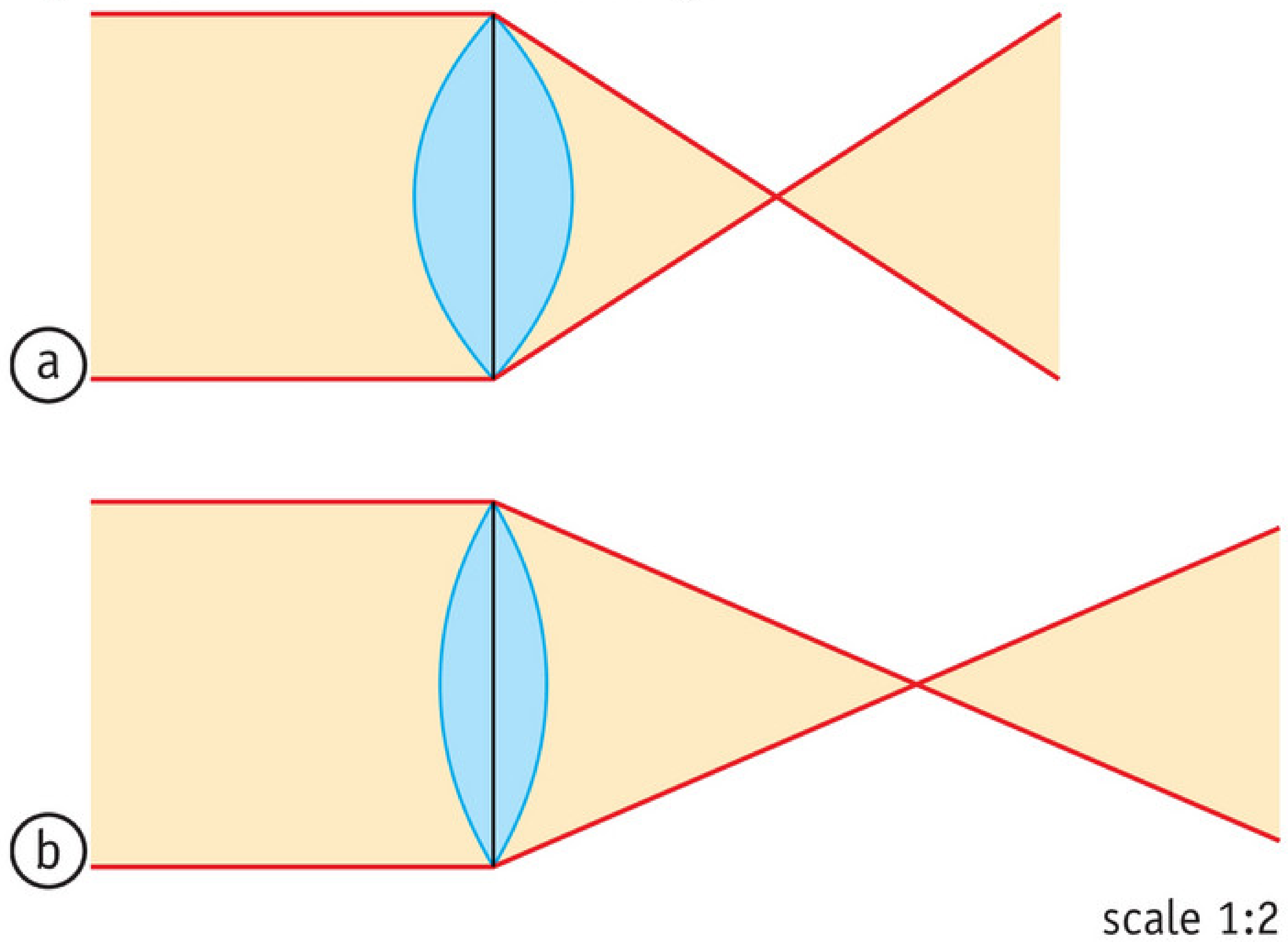
a What will she see on the paper if the spectacle lens is positive?
b What must Joyce do to set the paper on fire?

IN PRACTICE

3 Figure 8 shows cross-sections of two lenses.

a Which lens refracts the light most strongly?
b The scale of the drawing is 1:2.
Determine the focal length of each lens.

figure 8 Which lens is stronger?



4 The photo in figure 9 was taken with a camera that was set to *manual*.

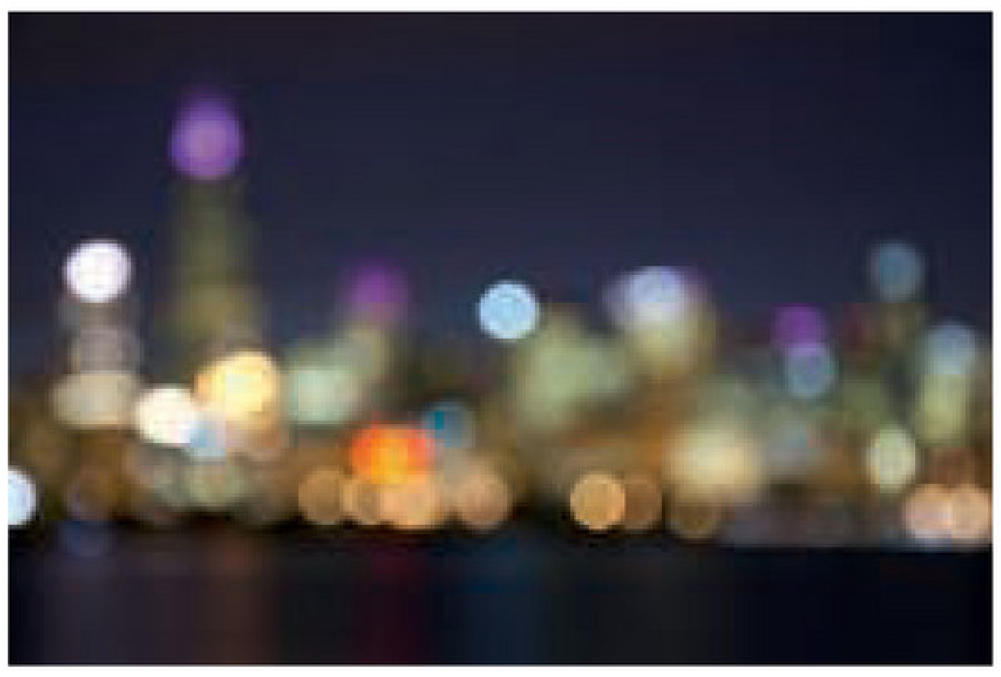


figure 9 The skyline of Chicago by night.

a How can you tell that the photographer had not focused the image properly?
b What objects are shown on this photograph as blurred circles of light?
c When the photo was taken, the distance between the lens and the image chip was greater than the image distance.
How would the circles of light change if the photographer made that distance even greater?
d How would the circles of light change if the photographer made that distance smaller and smaller?
e A modern camera focuses by moving the lens alternately back and forth with respect to the image chip.
Explain how the circles of light on the image chip will then change.
f When does the camera 'know' that the image is properly focused?

5

A lens creates a sharp image of an object O_1O_2 (figure 10).

a Construct the image of O_1 in figure 10.

b Draw in the image of O_2.

c Show in figure 10 where you would have to place a screen to get a sharp image.

d The object distance is .... cm. The image distance is .... cm.

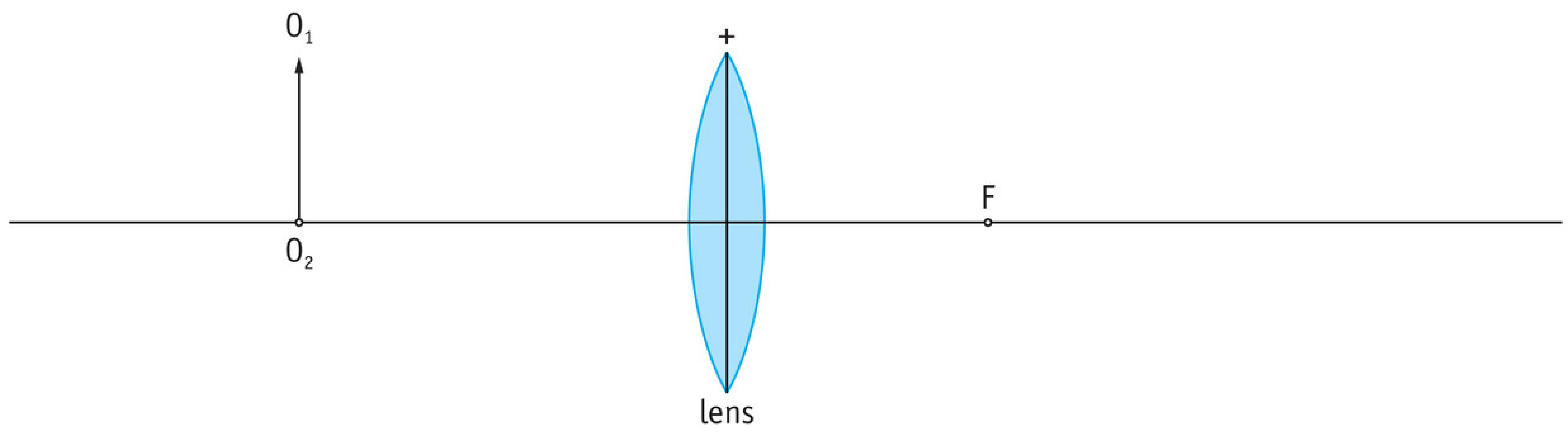


figure 10 A sharp image.

6

There is a bulb B in front of a lens (figure 11). You can see four rays hitting the lens.

a Which two rays are construction rays? *1 / 2 / 3 / 4*

b Sketch how the construction rays continue after the lens.

c Sketch how the other two rays are refracted.

d Suppose that someone places a screen close behind the lens and then moves the screen slowly to the right, until beyond the image distance.
Describe what they will see on the screen.

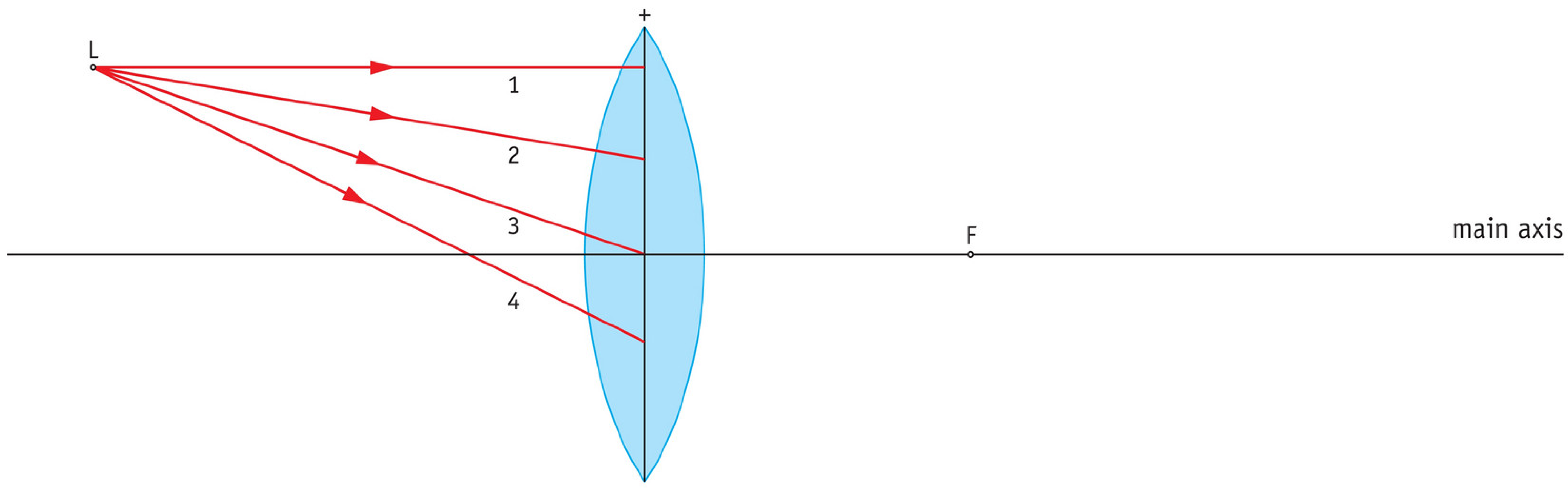


figure 11 What paths do the rays take?

★ 7

As part of an experiment, Abdul has placed a slide inside a light box. There is an arrow on the slide. Abdul moves the light box closer and closer towards a positive lens (figure 12).

a Use the construction rays to construct (i.e. draw) the position of the image I_1I_2 in each of the three drawings.

b How does the image change as the object is moved closer towards the lens?

c Investigate whether there is a directly proportional relationship between the object distance and the size of the image I_1I_2.

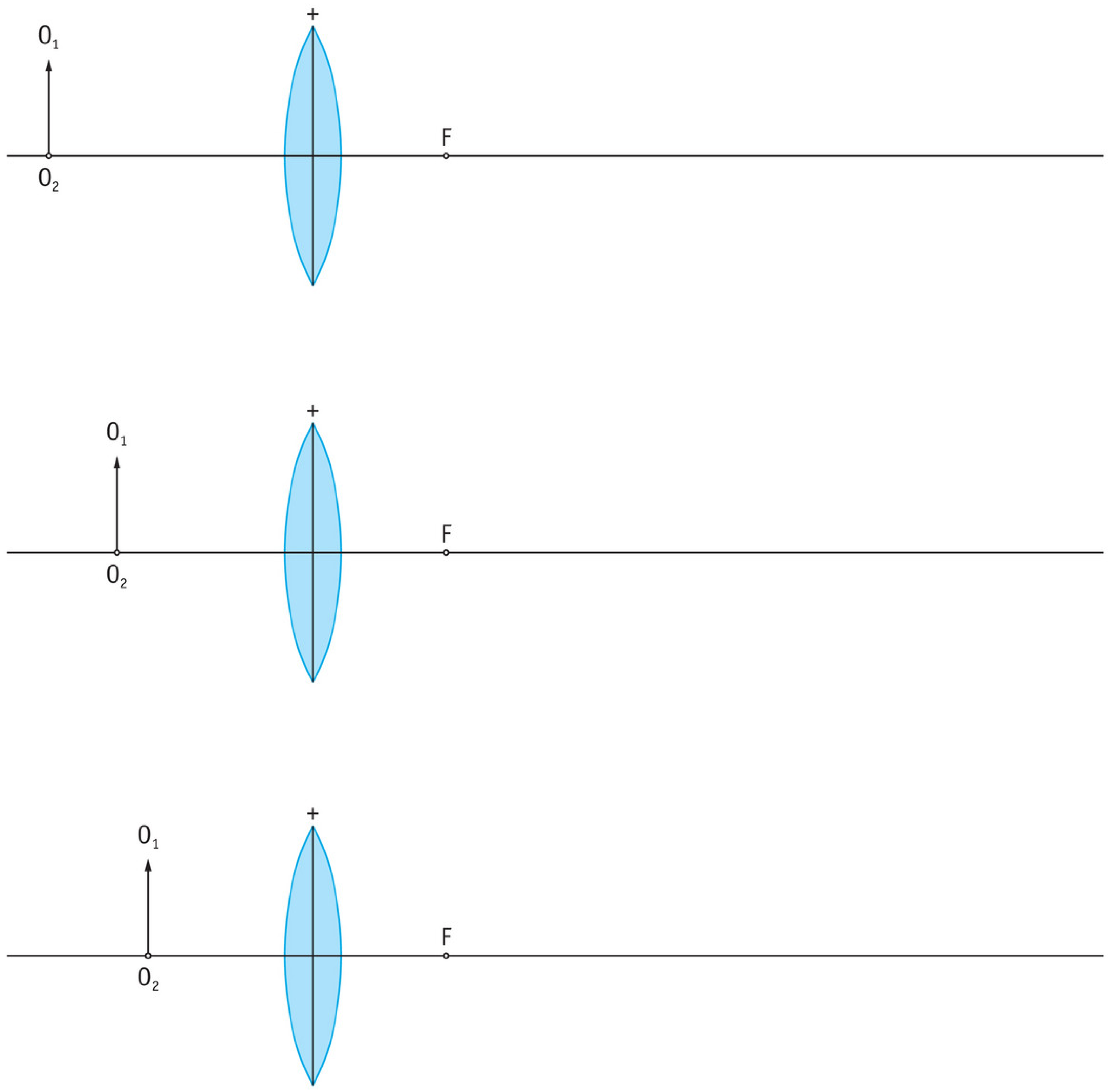


figure 12 Abdul's experiment.

★ 8

Melanie is using a lens (f = 10 cm) to project an image of an object onto a screen. At a given moment, the object is 15 cm in front of the lens.

a Draw this situation to scale and construct the image.

b You can calculate the magnification N using the formula $N = \frac{I_1 I_2}{O_1 O_2}$

By what factor is the image that you have constructed in Exercise (a) magnified?

c If Melanie makes the object distance v greater, the image distance b will become smaller. The image will become smaller too. The object is the same size as the image when v = 20 cm. What is the magnification factor then?

9

Amber creates an image of a candle flame on a wall using a large lens. After that, she replaces the large lens with a small lens that has the same focal length.

a Does this change the position of the image? If so, how?

b Does this change the size of the image? If so, how?

c Does this change how bright the image is? If so, how?

★ 10

Figure 13 shows how a positive lens refracts the light from a light source L. Determine the focal length of the lens using the data from the drawing.

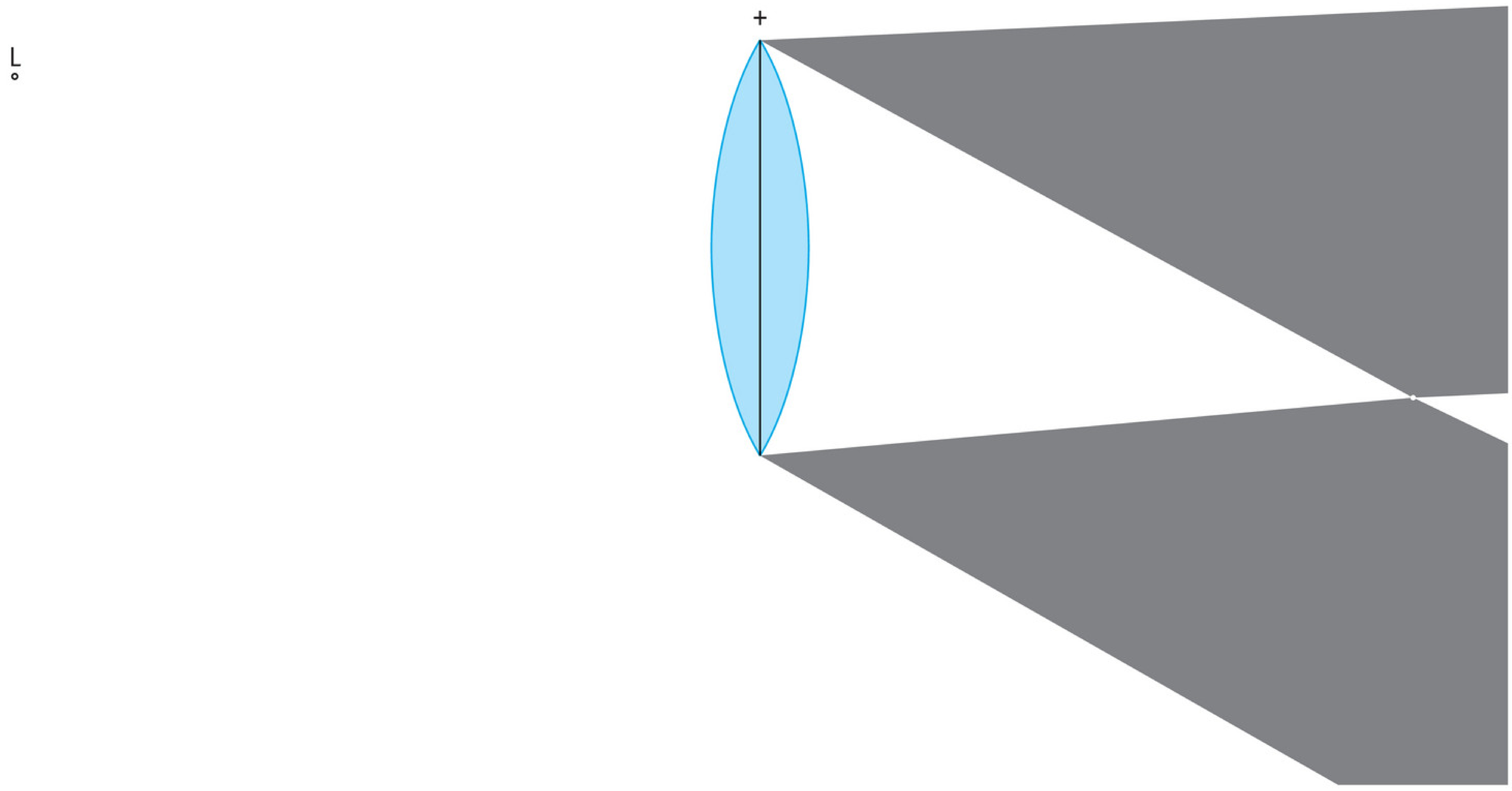


figure 13 Where is the focal point?

Test what you know with *Test yourself.*

PLUS REFRACTION IN LENSES

11 A ray of light hits a diamond at an angle of 30°.

a Explain whether light is refracted more or less strongly by diamond than by glass. Use table 1 for this.

b Calculate the angle of refraction.

12 A ray of light hits a glass lens. The angle of incidence *i* at the surface between the air and the glass is 45°.

a Calculate the angle of refraction *r*.

b When a ray of light from air hits a transparent substance and is refracted, we way that the ray is refracted *towards* the normal.
Explain what this means by comparing the size of the angle of incidence against the size of the angle of refraction.

c In figure 14, you can see on the right how the light then exits the lens again. If you want to calculate how light refracts at the transition from a transparent substance to air, a modified form of Snell's law has to be applied:

$$\frac{\sin i}{\sin r} = \frac{1}{n}$$

Assume that the angle of incidence $\angle i$ at the boundary from glass to air at the right-hand side in figure 14 is 39°. Calculate the angle of refraction $\angle r$ for the ray exiting the lens.

d When a ray of light is refracted from a transparent substance into air, the rule is that the angle of refraction is *greater* / *smaller* than the angle of incidence.
You then say that the ray is deviated *away from* / *towards* the normal.

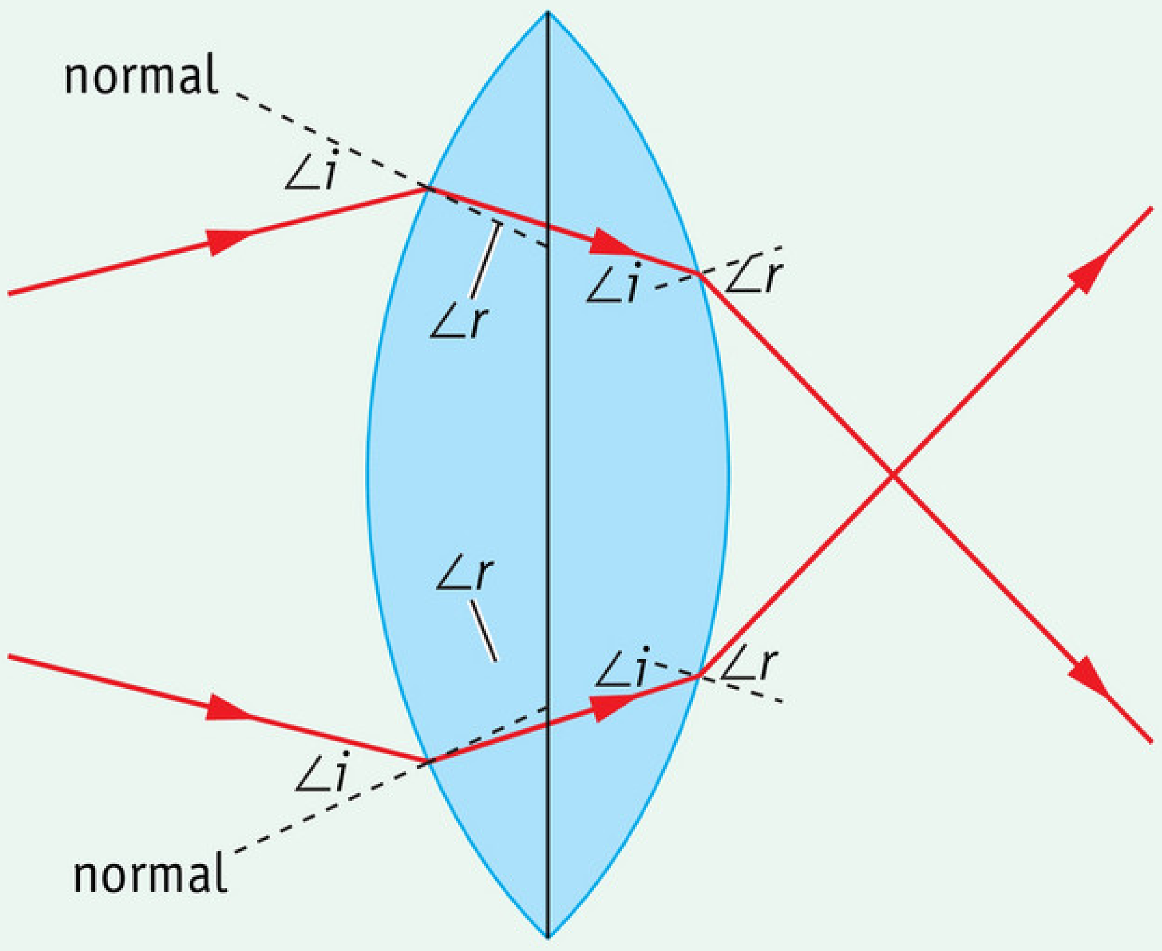


figure 14 Refraction through a lens.

3 Making X-ray photographs

LEARNING OBJECTIVES

6.3.1 You can explain what can happen when electromagnetic radiation hits an object (three possibilities).
6.3.2 You can describe how X-ray pictures are taken.
6.3.3 You can list the health risks of X-rays.
6.3.4 You can explain how the biological damage from radiation is expressed.
6.3.5 You can state and explain the safety rules for working with X-rays.
PLUS 6.3.6 You can explain how the various half-value layers of human tissues are used in medical imaging.

Unlike light, X-rays go straight through you. That makes it possible for images to be made of the situation inside the body. Thanks to modern technology, so little radiation is needed for making these photographs that the health risk is very low.

TRANSMISSION, REFLECTION AND ABSORPTION

When electromagnetic radiation falls on an object, three things can happen:

1. **Transmission**: the radiation passes through. You can see this with sunlight that passes through a glass window.
2. **Reflection**: the radiation is reflected back. You can see this when light is reflected by a mirror or a white wall.
3. **Absorption**: the radiation is absorbed. You can see this when a black curtain 'swallows up' sunlight and warms up.

These three processes often all occur at the same time. A pane of glass does not let all the light through that hits it. A fraction of the light is reflected by the glass and another fraction is absorbed.

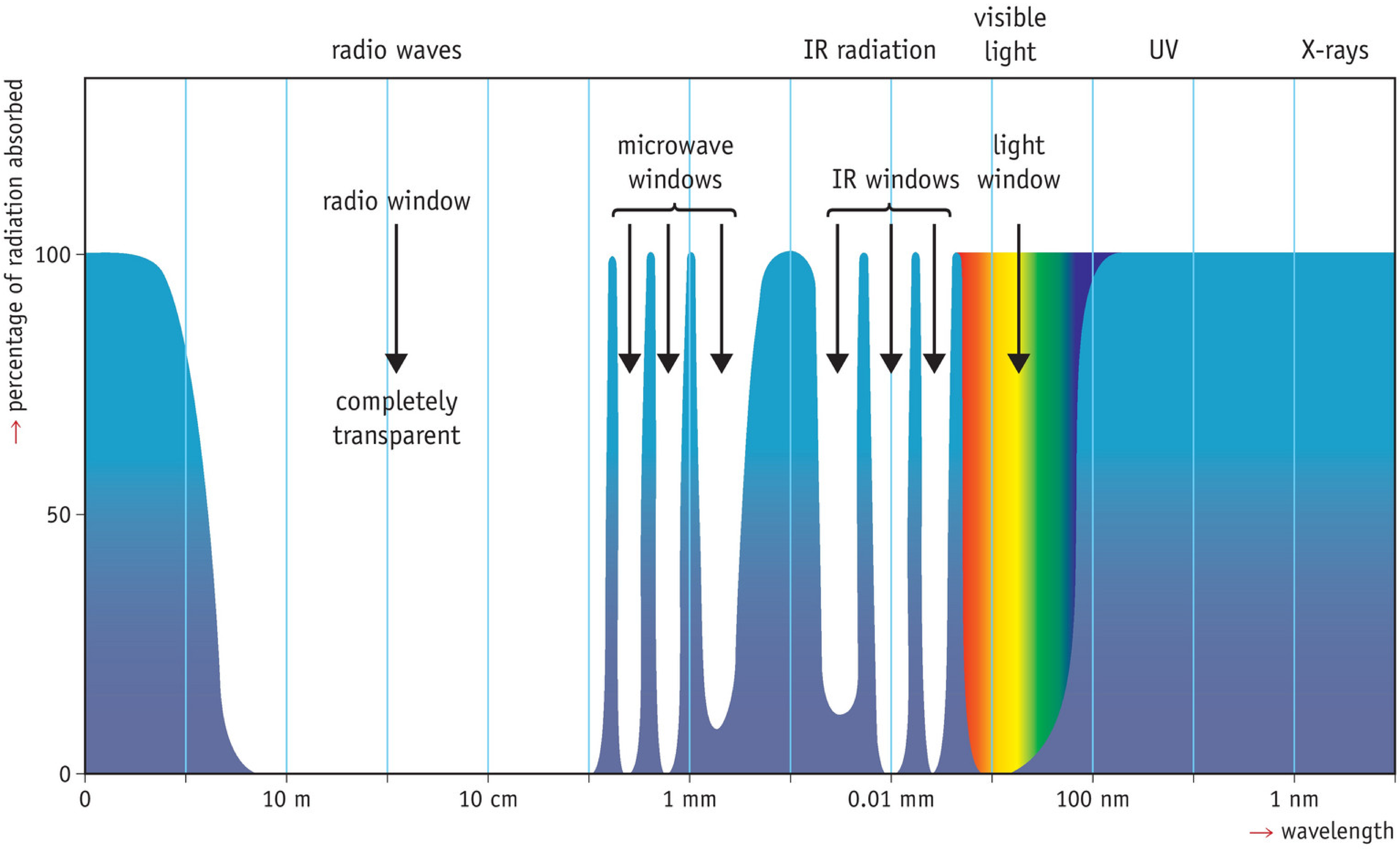


figure 1 The transparency of the atmosphere to various types of radiation.

The various types of electromagnetic radiation behave in very different ways. The atmosphere allows light through, for example, whereas gamma rays, X-rays and UV radiation with short wavelengths are absorbed. The ability of IR radiation and radio waves to pass through the atmosphere depends on the exact wavelength. The atmosphere is transparent to some types of radiation but completely opaque to others (figure 1).

When radiation hits the human body, the various types of radiation behave in different ways. Your body is opaque to light, for example: you cannot see through your hands or your chest. Light that hits your body is partially reflected and partially absorbed. X-rays can pass easily through the body, though. That property of X-rays makes it possible for images to be made of the situation inside the body.

IMAGING USING X-RAYS

Normal photographs are made using a lens. That is not possible with X-rays. There are two reasons why. Firstly, unlike light, X-rays are not reflected by objects. The radiation simply continues, penetrating the object. Secondly, X-rays are hardly refracted at the transition between two substances that are transparent (to X-rays). This means that there is no good way of using a lens to focus X-rays.

An X-ray photograph therefore has to be made using a different principle (figure 2). An **X-ray source** is placed on one side of the body part that is to be examined and a **detector screen** is placed on the other side of the body part. When a photo is taken, the source emits a brief flash of X-rays. The soft tissues let most of this radiation pass, whereas the bones absorb a lot of the radiation. A shadow image of the bones inside the body is therefore left on the screen and recorded by the detectors.

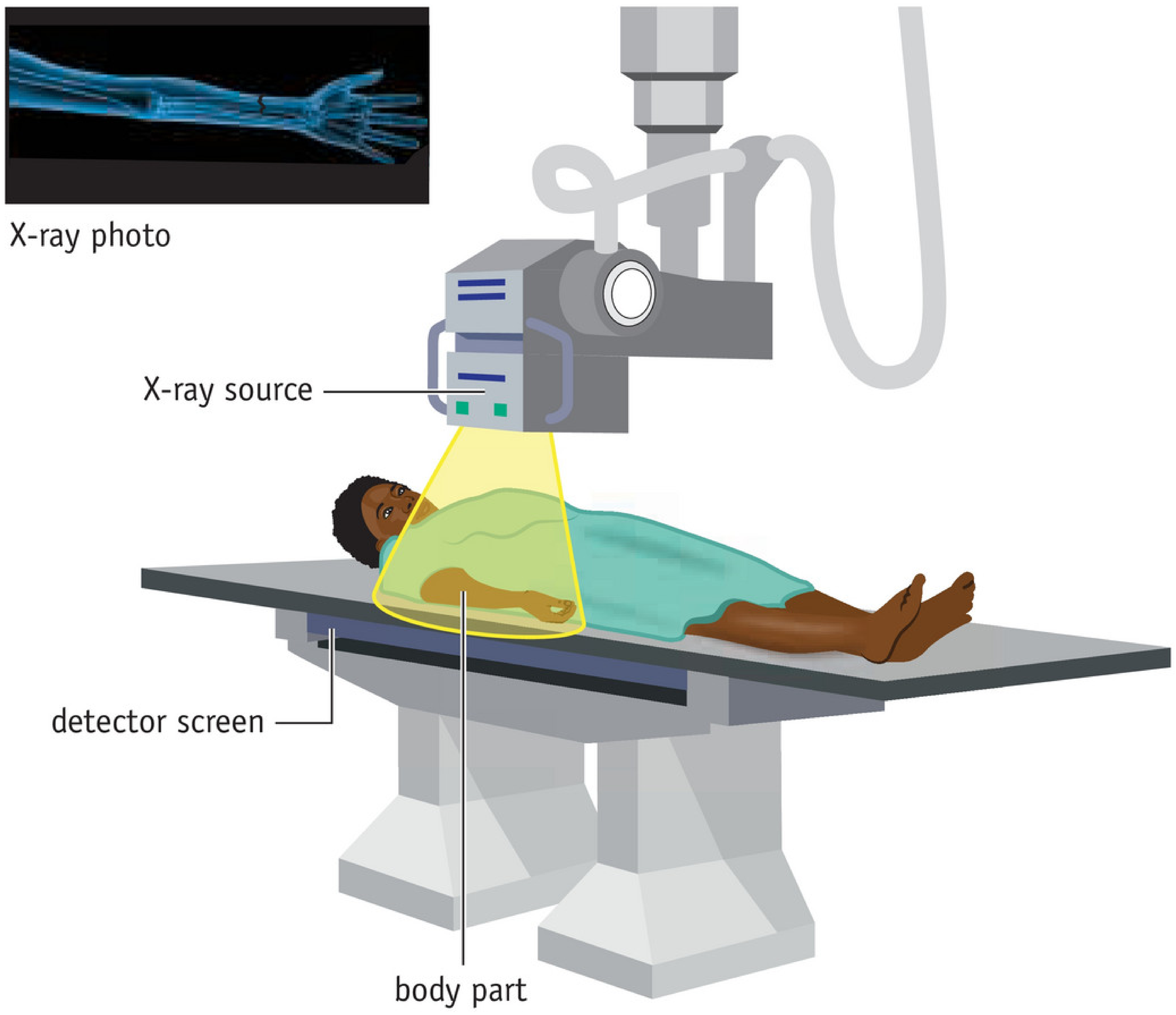


figure 2 This is how X-ray photographs are made.

X-rays are generally shown as negatives (figure 3). This means that the shadows left by the bones (for which the transmission is low) show up white against the surrounding tissue (which transmit well). At first, that wasn't a deliberate choice: photographic film was used, which created negative images when the film was developed. But modern equipment produces digital images that could equally well be shown as positives. Doctors still generally prefer the negatives, though, because the details are reckoned to be more easily visible that way.



figure 3 An X-ray picture of a broken upper arm in which a metal plate has been inserted. The shadow of the metal is even lighter than that of the bone.

HAZARDS OF X-RAYS

The German physicist Wilhelm Röntgen discovered X-rays in 1895 (figure 4). Doctors were quick to make use of his discovery. They used X-rays to examine bone fractures, for instance. It was commonplace at the time for the doctor to hold the broken body part in place so that it did not move while it was being irradiated. This meant that the doctors were getting irradiated every time as well.



figure 4 Röntgen grew up in the Netherlands. This plaque is on a house in Utrecht where he lived when he was studying there. On the left, you can see his first X-ray photograph, of his wife's hand.

It soon became clear that repeated exposure to X-rays caused health problems. The first sign of that was a persistent red rash on the skin. Over the course of time, many doctors developed cancerous swellings (tumours) at the irradiated sites. Their hands were mostly affected first because that was where the exposure to the radiation was greatest.

The problems were made worse by the fact that the detector materials were not very sensitive, so large amounts of radiation had to be used. Better techniques were developed later. As a result, much less radiation is needed for making X-ray photographs nowadays. But even small amounts of X-rays affect the body.

DETERMINING THE DOSE

When an X-ray is made, part of the radiation goes straight through the body. That radiation does not do any harm, because it has not passed any energy on to the body. This fraction of the radiation is unchanged as it goes through the body. The damage is caused by the radiation that is absorbed by the body and releases its energy there. It is that release of energy that can break important molecules such as DNA.

If you want to know how much damage has been caused, you look at the amount of radiant energy that the body has absorbed. This is then used to determine the **equivalent dose**. This is a measure for the biological damage that has been caused. The unit for this is the sievert (Sv). An equivalent dose of 1 Sv gives roughly a 5% greater chance of getting cancer at some future time.

The sievert is used for all types of ionising radiation, not just for X-rays (figure 5). This makes it possible to compare the levels of risk. Taking a chest X-ray means you get a dose of 0.1 mSv, for example. That is the same as the amount you get from cosmic rays high in the atmosphere during a flight from Amsterdam to New York and back. Both activities result in the same, small risk.

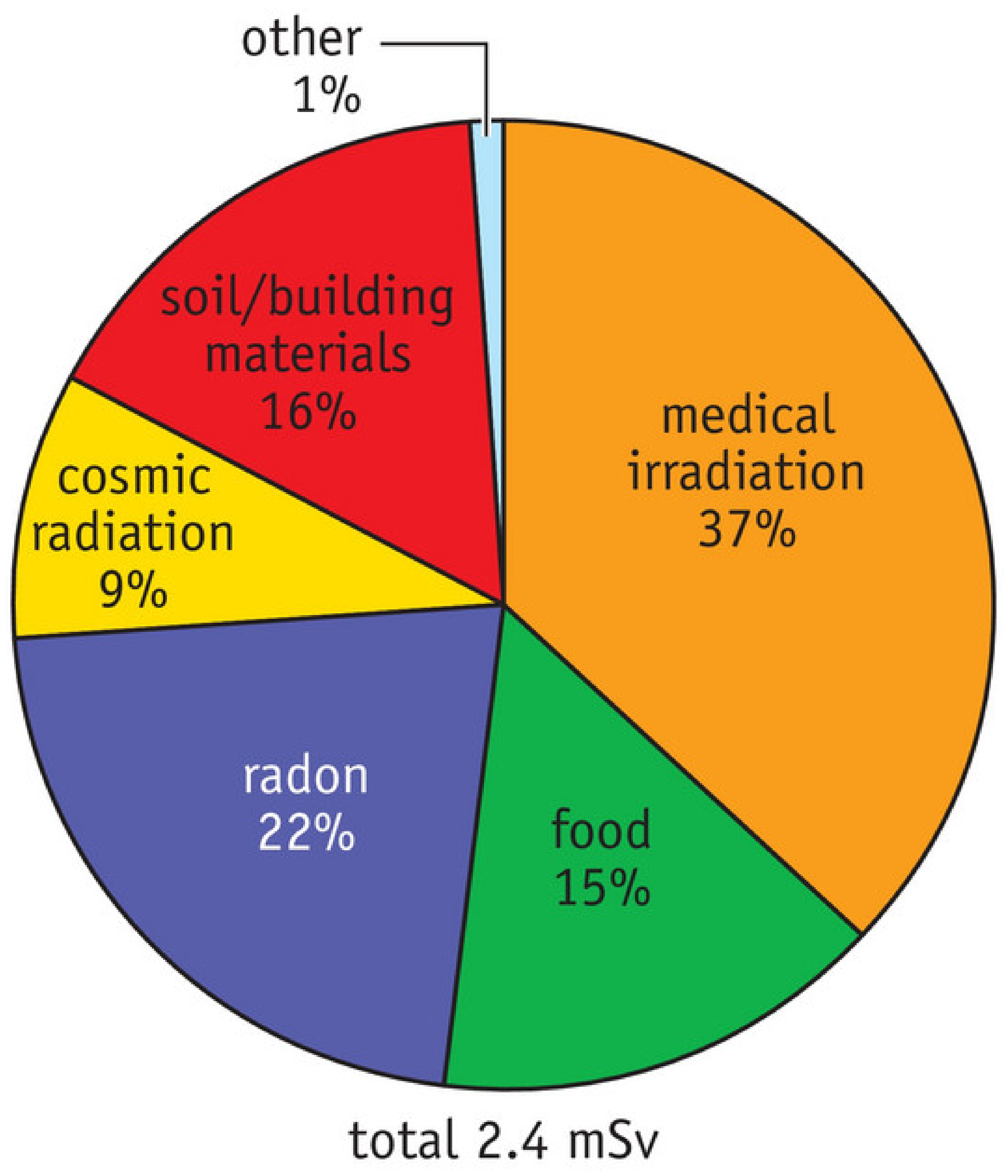


figure 5 The average radiation burden per person per year in the Netherlands (source: RIVM).

PROTECTION AGAINST RADIATION

Every time that someone is exposed to X-rays, there is damage to the body. The risk that this will ever lead to problems becomes greater with each exposure. So people who work with X-rays every day have to be protected against them. If they regularly get small doses of radiation during their work, it can add up to an unacceptable risk over the course of time.

There are therefore strict safety rules for working with X-rays. The principle is always that the employee must never be irradiated themselves. They must therefore keep a substantial distance away when taking X-rays. Radiation spreads out as it gets further from the source and so it becomes weaker and weaker. X-ray equipment is therefore always operated remotely.

For the laboratory technician taking the X-ray pictures in a hospital, just keeping out of the way is not enough. So people with that job stand behind a wall that has a lead lining when they are taking the photos. The glass that the lab technician watches through also contains lead (figure 6). Very dense substances are the most effective at absorbing radiation. Because lead (ρ = 11.3 g/cm^3) is relatively cheap, it is the most widely used screening material.

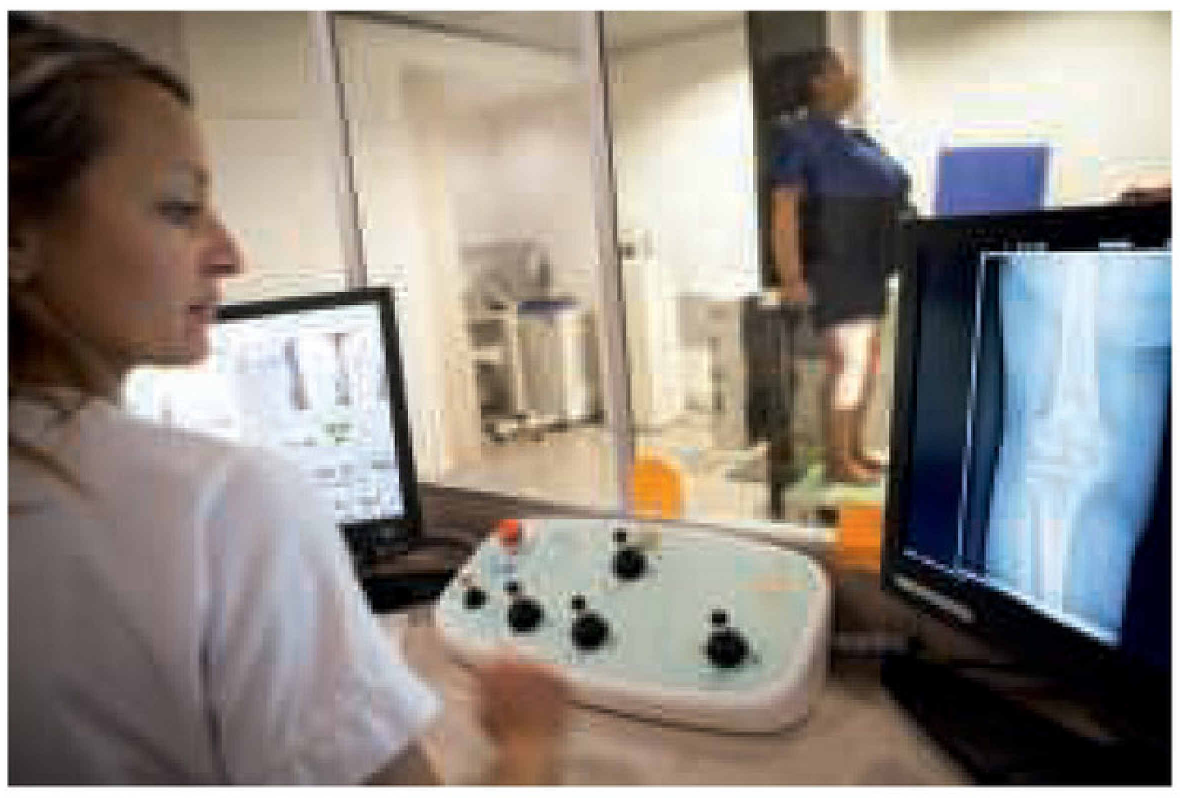


figure 6 Taking an X-ray in a hospital.

PLUS HALF-VALUE LAYER

Gamma rays and X-rays are never fully absorbed by an object. A bit of radiation always passes through. The **half-value layer** $d_{½}$ shows how much radiation an object absorbs. If you make an object of the same thickness as the half-value layer, the intensity I of the radiation will be halved (figure 7). If you make the object twice as thick (two half-value layers), the intensity of the radiation passing through will be ½ × ½ = ¼ of the original intensity. 25% of the radiation intensity then remains, meaning that 75% has been absorbed by the material. Every material has its own specific half-value layer, with the thickness depending on the type of radiation falling on it (table 1).

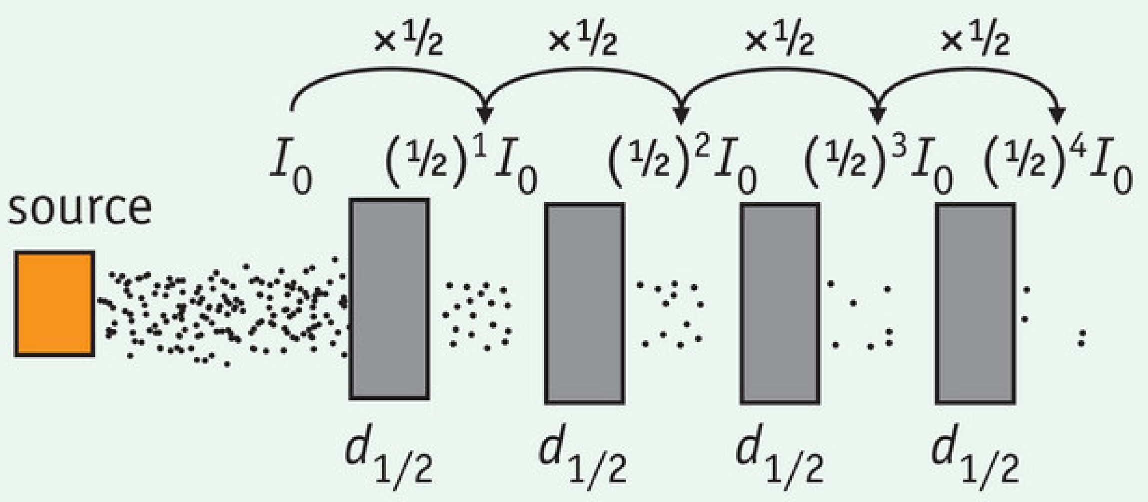


figure 7 The intensity of the radiation is halved for every half-value layer.

table 1 The half-value layer thicknesses of various materials for X-rays and gamma radiation.

material	half-value layer for X-rays (cm)	half-value layer for gamma radiation (cm)
air	2.8·10^3	20.8·10^3
muscle tissue	3.08	22.9
bone	1.08	12.6
lead	0.0079	1.44

Practice the concepts using the *Flash cards*.

COURSE MATERIAL

1

Answer the following questions.

a What three things can happen to radiation that falls on an object?

b Why are bones clearly visible on an X-ray photograph?

c What is meant by the 'equivalent dose'?

d What units are used for measuring the equivalent dose?

2

Figure 8 shows an X-ray photo of a man's neck.

a Explain why the object in his throat is so clearly visible.

b Place the following objects that you can see in figure 8 in order from low to high X-ray absorption: *bones – clothing – air – muscle tissue– object.*



figure 8 An X-ray of the neck of a man with a foreign object that doesn't belong there.

IN PRACTICE

3

Luggage is often checked at airports using X-rays. Figure 9 shows a sketch of this type of check, with the X-ray source and a suitcase on the conveyor belt.

a Explain where the X-ray camera is located: at A, B, C or D?

b Why do the intensity and duration of the irradiation not need to be monitored as closely for this kind of check as for X-rays taken at a hospital?

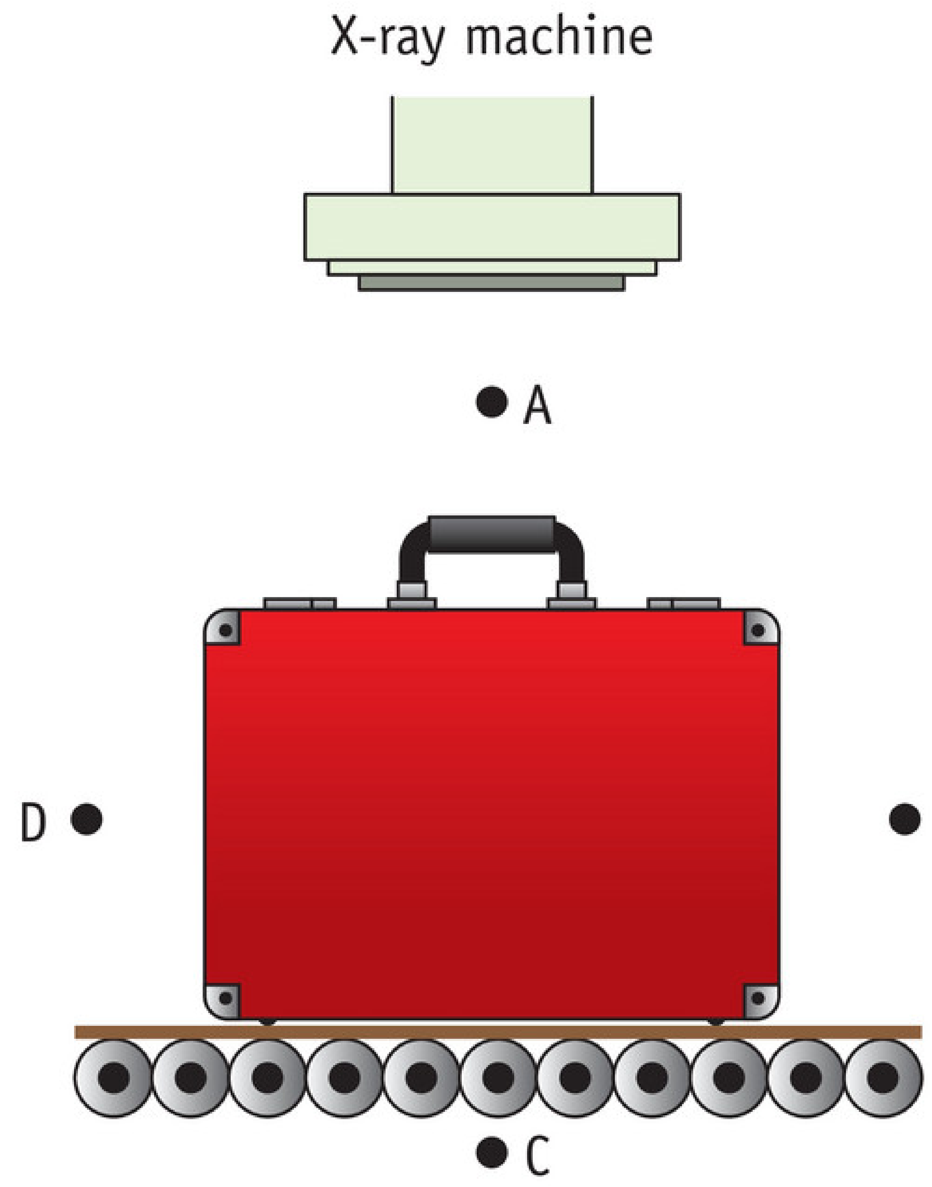


figure 9 Luggage being checked at an airport.

4

The bones in your body are complex organs with their own specific structure. Tip: before starting this exercise, Google up some images for the words *x-ray leg*.

a What would the bones look like on an X-ray if they were completely solid?

b In reality, bones are hollow rather than solid. There is a soft tissue inside called the bone marrow.
Explain how you can tell that from an X-ray.

5

Dentists often take X-rays of the teeth (figure 10).

a Explain why X-rays are a useful tool for dentists.

b Do the fillings allow a lot of radiation to pass or just a little? Explain your answer using figure 10.

c Which part of the teeth and gums lets the most radiation through?

d When an X-ray is being taken, the dentist first leaves the treatment room and the photo is taken remotely.
Why do they do that?

e The dentist suggests making a 'panorama photo' of all your teeth once every five years.
Write down one benefit and two disadvantages of this.

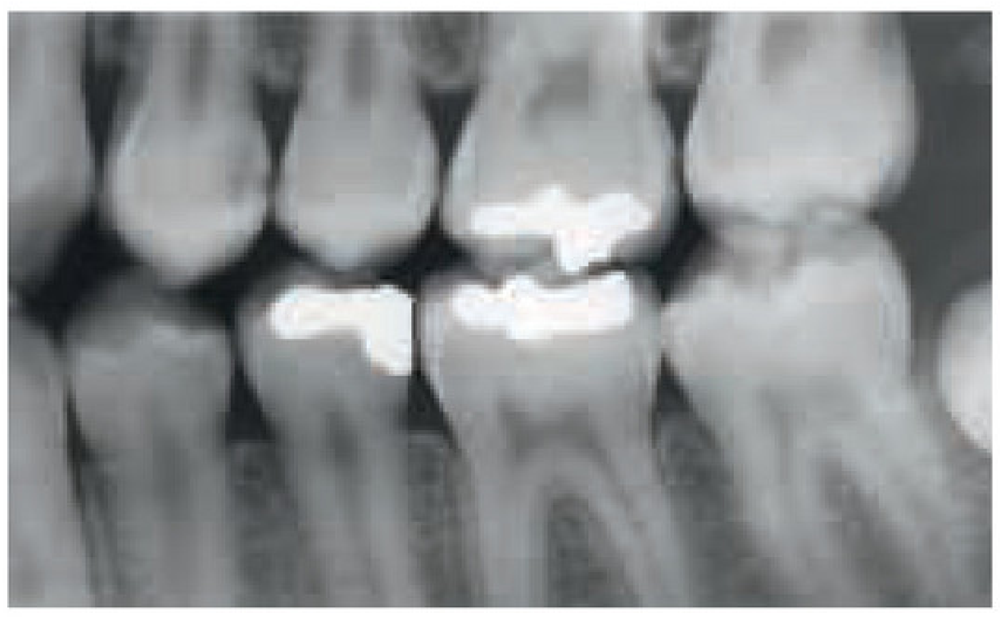


figure 10 An X-ray of the teeth.

6

A medical encyclopaedia contains a short article about X-ray contrast images (figure 11). Read the article and answer the questions.

a Explain why the intestines cannot be seen on a normal X-ray.

b Explain why you can see the intestines after the patient has swallowed barium sulphate.

c There is another organ that can be imaged using barium sulphate.
Work out for yourself which that is.

X-ray contrast

It is not possible to produce images of the intestinal wall using X-rays. To visualise any abnormalities, a layer of barium has to be deposited that does not allow X-rays to pass. Barium sulphate is mixed with water and given as an enema or swallowed. Barium given by enema will be in place in 25 minutes; barium that is taken orally takes five hours.



figure 11 Information about an X-ray contrast photo of the intestines.

7 When flying at high altitudes, plane crews are exposed to cosmic radiation (ionising radiation from space). According to EU rules, the extra dose must not be higher than 6 mSv a year.

a Explain why the rules say that it is acceptable for aircraft crews to receive this extra dose.

b Everyone in the Netherlands absorbs 2.4 mSv a year on average from all kinds of sources. A flight from Amsterdam to Tokyo results in an extra dose of 0.075 mSv.
By what percentage is your dose increased by a return flight between Amsterdam and Tokyo? Do you think that is a lot?

c The maximum extra dose for pregnant crew members is 1 mSv.
Explain why the maximum is lower for pregnant women.

d How often is a pregnant stewardess allowed to make a return flight between Amsterdam and Tokyo?

8 The Radiology department of a hospital is responding on its website to some frequently asked questions. Figure 12 shows you one of those questions and the hospital's response.

a The answer mentions an apron that is intended to protect the baby.
What material does this apron probably contain? Why?

b Sometimes it may be possible to see part of the apron on the X-ray.
Explain what 'colour' the apron will have on the X-ray photograph.

figure 12 A frequently asked question about X-ray examinations.

Can I be given an X-ray examination if I am pregnant?

If you are pregnant or think that you might be pregnant, you must tell the doctor who is treating you. They can then decide in consultation with you whether to go through with the investigation or whether it should be done at a later date, or whether an alternative examination should be used.
If your investigation has already been agreed on, tell the administrative staff at the Radiology department or the radiology technician that you are pregnant before the examination takes place. There are then three options:

- The examination will be postponed until after the birth.
- The doctor will propose a different kind of examination to you.
- You will be given a special apron to wear that will protect your baby against the radiation.

★ 9 The website www.radiologen.nl compares the risk of X-ray examination against other risks. According to the site, these are the average losses in life expectancy as a result of:

- alcohol abuse: 11 years
- smoking: 6.3 years
- passive smoking by a partner: 2.7 years
- 20% overweight: 3.0 years
- 10 mSv annually: 1.5 months

a The figures on the website are based on the lifetime exposure from the start of adulthood.
Explain why this assumption is not very realistic for X-ray examinations.

b Explain what conclusions you can draw from this study about the risk of a normal X-ray, for example of your heart and lungs.

c More radiation is needed for other forms of X-ray examination. A chest CT scan requires a dose of 9 mSv, for example.
Does this mean that examinations of this type reduce your life expectancy by almost 1.5 months?

d A one-off dose of 9 mSv is practically harmless if someone is 90 years old. Explain why.

Test what you know with *Test yourself*.

PLUS HALF-VALUE LAYER

10 Study table 1.

a Explain why the half-value layer for a material is thicker for gamma radiation than it is for X-rays.

b Explain the difference in half-value layer thicknesses for air and muscle tissue.

c The density of air is 1.3 kg/m^3 and for lead the figure is 11.3 g/cm^3.
Investigate whether the half-value layer for a substance is inversely proportional to the density for both X-rays and gamma rays.

11 Table 1 states the half-value layer for lead.
Hospitals use lead aprons (figure 13) to prevent staff who work with X-rays from absorbing too much radiation. A standard lead apron contains a layer of lead that is 2.0 mm thick.

a Explain whether the lead apron would absorb more or less than half the radiation if it was used for gamma radiation.

b Explain why the standard lead apron is used against X-rays but not against gamma radiation.

c By what percentage is the intensity of gamma radiation reduced if the gamma source is in a lead jar with walls that are 4.32 cm thick?

d How thick would the walls of the jar have to be in order to reduce the intensity by 93.75%?



figure 13 The intensity of the radiation is halved by the lead apron for every half-value layer thickness.

12 The fact that the half-value layer is different for different substances is used when X-ray photographs are taken.

a Explain this using figure 10.

b When you see a white spot on a grey area in an X-ray, it can be because there is another substance there with a different half-value layer. There is also another possible explanation.
Explain what else could be causing it.

4 Working with gamma radiation

LEARNING OBJECTIVES

6.4.1 You can describe what the terms ‘radioactivity’ and ‘half-life’ mean.
6.4.2 You can calculate the activity of a substance after *N* half-lives.
6.4.3 You can determine the half-life from a graph of the activity against time.
6.4.4 You can describe the three types of radiation that are emitted by radioactive substances.
6.4.5 You can describe the penetrating power of the various types or radiation.
6.4.6 You can describe how medical research is carried out using gamma radiation.
6.4.7 You can explain the difference between contamination and irradiation and how they are applied.
PLUS 6.4.8 You can describe the difference between internal and external irradiation and state what their health effects are.

Radioactive substances emit radiation. This radiation is used at hospitals to detect and treat diseases. Careful attention is paid to safety because the radiation can also make healthy people sick.

RADIOACTIVITY

In 1896, the French physicist Henri Becquerel (1852-1908) discovered that some substances spontaneously (in other words, of their own accord) emit strongly ionising radiation. These are called **radioactive** substances. The prefix ‘radio’ comes from ‘*radius*’, the Latin word for a ray, and ‘radioactive’ means ‘emitting rays’.

You can find radioactive substances everywhere, but mostly in small amounts: in the soil, in water, in the air, in the walls of buildings and even in your own body. A lot of these substances are natural in origin (figure 1): they are said to be **naturally radioactive**. Since 1896, physicists have learned how to create new radioactive substances themselves; these substances are said to be **artificially radioactive**.



figure 1 Brazil nuts are known to contain small amounts of radium, a naturally radioactive substance.

During this process, a radioactive substance is gradually converted into another substance. After a certain time, half the original quantity of the substance will have disappeared. The amount of radiation will therefore also have halved. The time needed for this to happen is called the **half-life** (figure 2).

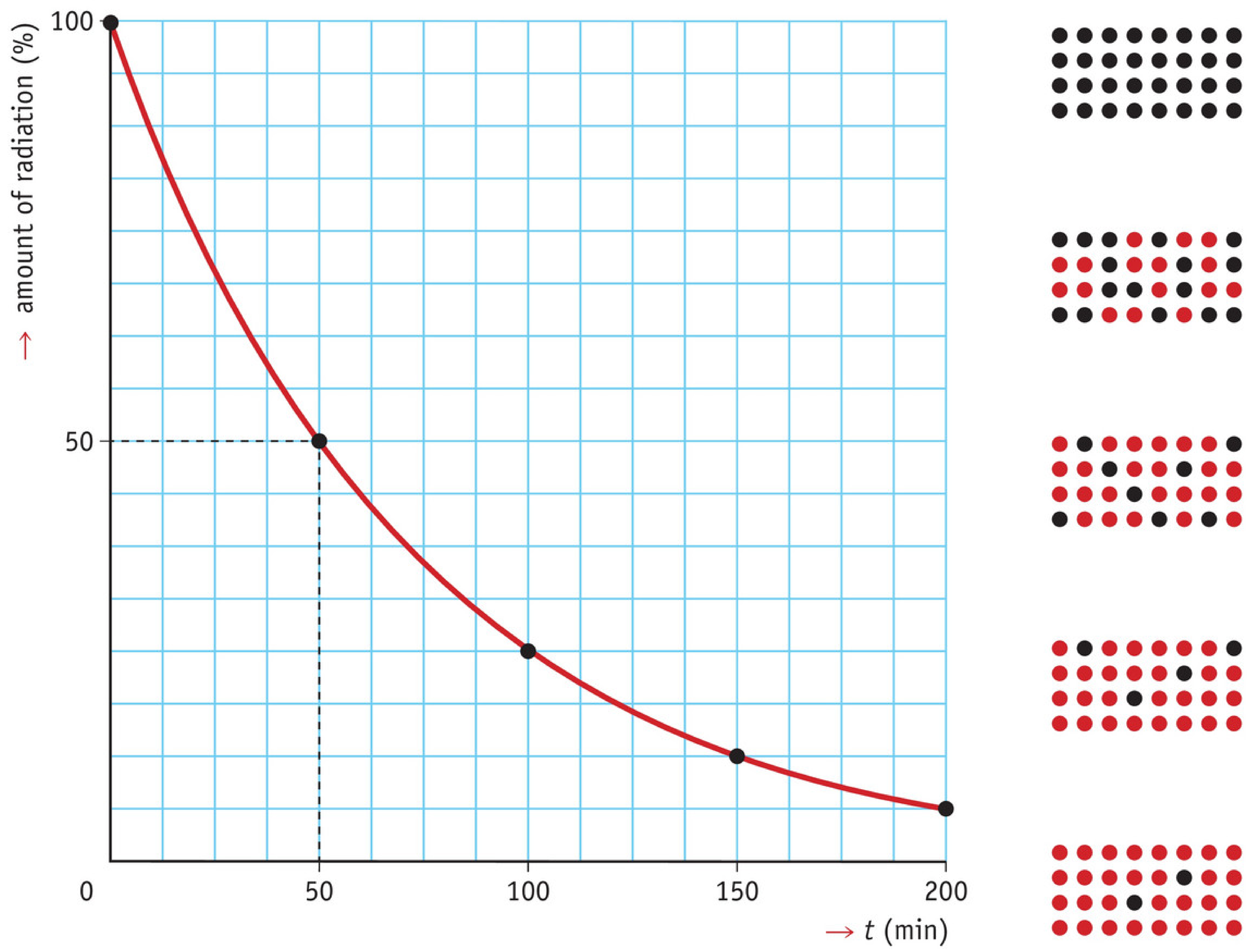


figure 2 The amount of radiation from a radioactive source with a half-life of 50 minutes.

Radioactive substances can have very different half-lives. There are naturally occurring substances with half-lives of billions of years. Artificial radioactive substances with half-lives ranging from hours to weeks are used at hospitals. These substances disappear quickly after an examination or treatment is finished, so that they do not present a risk any more in the longer term.

THREE TYPES OF RADIATION

Radioactive substances can emit both particles and electromagnetic waves. The particles and the waves move away from the radioactive substance in all directions (figure 3). That is why the particles and the waves are both called radiation, although they are totally different phenomena in physical terms. Both the particles and the waves are ionising.

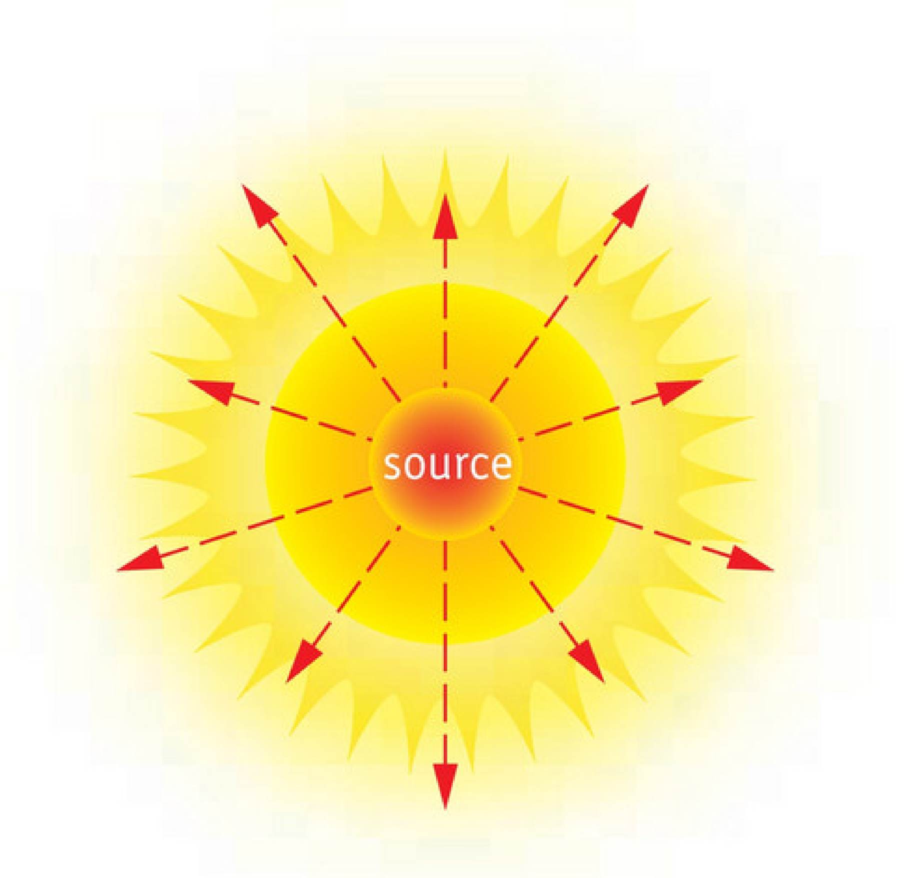


figure 3 You could draw this image for any type of radiation.

Particle radiation consists of a stream of particles that move very fast, like bullets out of a gun. The speed and the mass are what give the particles their ionising effect. They can easily damage a molecule when they collide with it. Physicists distinguish two types of particle radiation: **alpha radiation** (α-radiation) and **beta radiation** (β-radiation). Alpha particles are much larger and heavier than beta particles.

Some radioactive substances emit alpha radiation and others emit beta radiation. Electromagnetic radiation with a very short wavelength is usually emitted along with the particle radiation. This radiation is called **gamma radiation** (γ radiation) or gamma rays. Gamma radiation is very similar to X-rays, in terms of the health effects as well, but it is even more strongly ionising.

PENETRATING POWER

Alpha and beta particles can penetrate a certain way into substances, losing their kinetic energy as they go through collisions with the molecules in the substance. The maximum distance they can travel is known as the **penetration depth**. The penetration depth is different for every type of radiation and also varies from one substance to another.

Alpha radiation only penetrates a small way. A sheet of paper or a few centimetres of air are enough to block the stream of alpha particles. These particles cannot penetrate the outermost layer of your skin either. Beta radiation penetrates further than alpha radiation. But a 4 mm sheet of aluminium can block the stream of beta particles; they cannot pass through a thick book, either.

Gamma radiation has a much greater **penetrating power** than alpha or beta radiation. This radiation goes straight through substances, so you cannot really say that it has a penetration depth. The radiation gets weakened as it penetrates further into a substance, but the intensity never falls completely to zero. A layer of lead several centimetres thick, or an even thicker layer of concrete, is needed if the gamma radiation is to be weakened sufficiently.

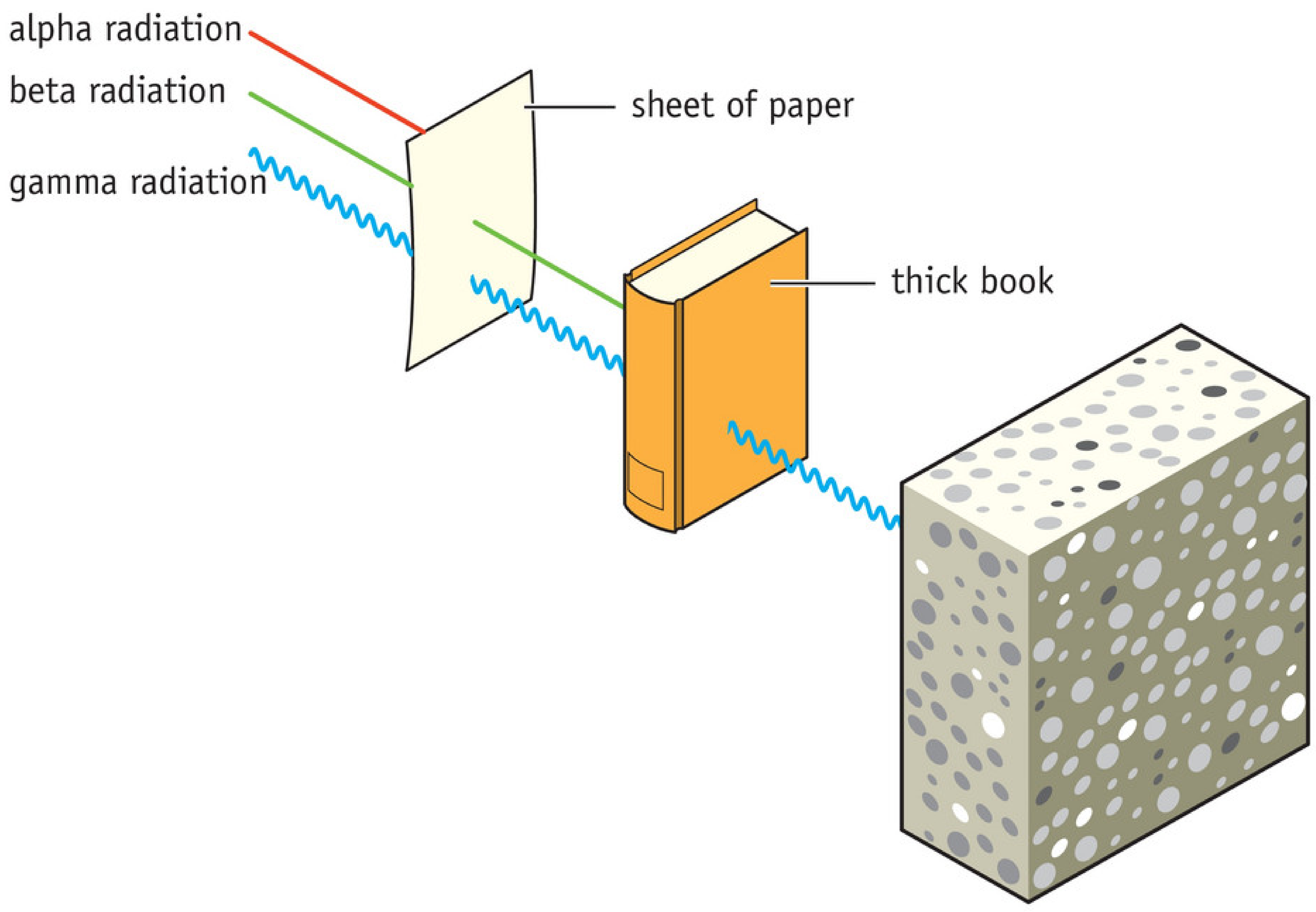


figure 4 The penetrating power of alpha, beta and gamma radiation.

EXAMINATIONS USING GAMMA RADIATION

Gamma radiation is used in the hospital to make **scans** of organs. This type of scan shows how a radioactive substance is distributed in an organ. Because gamma radiation has high penetrating power, it goes through the body easily and can then be detected outside the body. This is not possible with alpha and beta radiation.

Figure 5 shows you how an examination using gamma radiation works.

1. A laboratory makes a **tracer** (a radioactive marker substance). The artificial radioactivity of the molecules of the tracer makes them visible to gamma detectors.
2. The tracer is then put in the patient's body. This is usually done with an injection. The tracer spreads through the body, ending up in the organs that are to be examined.
3. The gamma radiation emitted by the tracer is recorded by a **gamma camera**. This is a disc of detectors that is moved in an arc around the patient. The detectors only 'see' gamma radiation that hits them perpendicularly to the detector surface.
4. A computer uses the measurement data from the detectors to construct an image of the organ. This is a *false-colour image* – one that uses different colours to represent the intensity of the radiation. Red is generally used for the highest radiation level and blue for the lowest.

figure 5 Making a scan.



a A tracer is made in the laboratory.



b The tracer is injected into the body of the patient.



c The gamma camera registers the release of radiation.

Figure 6 shows you the result of a thyroid examination. The tracer used is a substance that the thyroid gland absorbs from the blood. The computer image shows where the tracer has ended up. It is clear that part of the thyroid gland is not working properly: the right-hand half has taken up less of the tracer than the left-hand half.

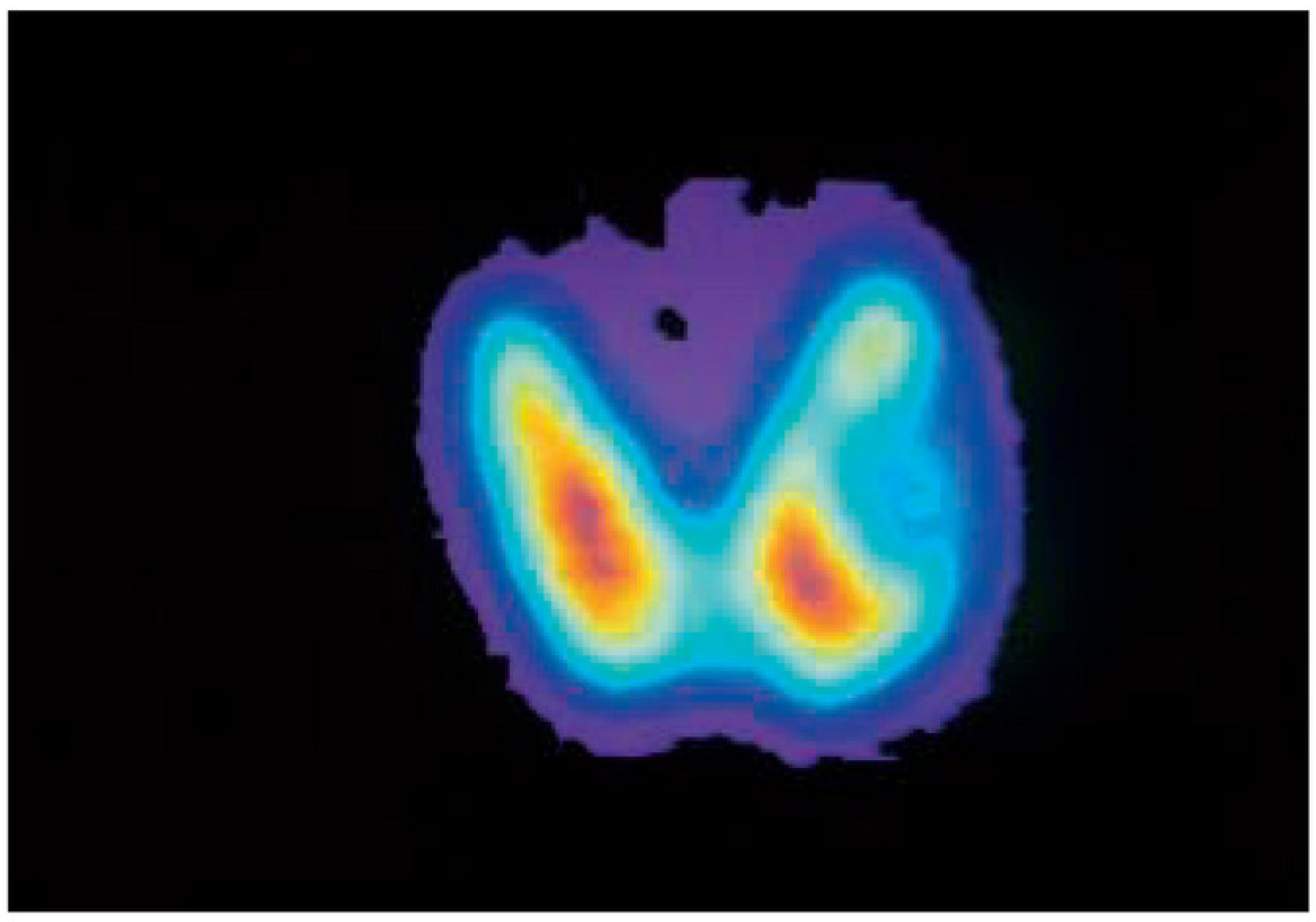


figure 6 A false-colour image of a thyroid gland.

IRRADIATION AND CONTAMINATION

X-rays are produced by a device that only emits radiation when a button is pressed. Alpha, beta and gamma radiation are emitted all the time, though, even when the radioactive source is not being used. This means that you are always running the risk that your body could be irradiated if you are near to a radioactive source.

The high penetrating power of gamma radiation means that it is by far the most dangerous. Radioactive sources that produce gamma rays therefore need to be screened off thoroughly. As for X-rays, lead is often used for this because it absorbs gamma radiation strongly (figure 7).



figure 7 A container for transporting radioactive substances. The inner and outer walls are made of steel. Between them is a thick layer of lead.

If you are irradiated from outside, this does not make your body radioactive, even though damage may be caused inside you. Radioactive substances can however also end up *inside* your body, through the air that you breathe, the water that you drink and the food that you eat. They can also end up on your skin. This is called **radioactive contamination**. The result is not only radiation damage to your body, but that your body becomes a radioactive source too.

The purpose of a lot of the safety rules for radioactivity is preventing contamination (figure 8). For example, you must not eat, drink or smoke near radioactive sources, and you must always wash your hands after you have worked with radioactive substances. If you get contaminated, you have to take off your contaminated clothes and take a shower. This lets you rinse the radioactive material off your skin and out of your hair.



figure 8 You must wear a protective suit when taking samples of water that may potentially be radioactively contaminated.

PLUS RADIOTHERAPY

Radioactive sources are not only used for making diagnoses but also in the treatment of tumours. Using radiation to destroy cancer cells is called **radiotherapy**. Radiotherapy is often used in treating cancer, usually in combination with surgery and chemotherapy.

When the tumour cells absorb radiation, the DNA in the cells is damaged. Once the DNA becomes too damaged, the cell is no longer able to divide and it dies off. Unfortunately, the same is true for healthy cells. It is therefore important to target the radiation so that as many tumour cells are irradiated as possible and as few healthy ones as possible.

External irradiation

In **external irradiation**, the radioactive source is outside the body. The source emits X-rays or gamma rays. During the treatment, the source is rotated around the patient so that the radiation is not always coming from the same direction (figure 9).



figure 9 A device for external irradiation. The radioactive source is above and to the left of the patient.

Internal irradiation

In **internal irradiation**, the radioactive source is located inside the body. The radioactive substance is packaged into tiny metal rods (figure 10) that a doctor implants into the tumour. Substances that emit gamma or beta radiation can be used for this. At the end of the treatment, the rods are removed again.



figure 10 Rods that are used for internal irradiation.

Practice the concepts using the *Flash cards*.

COURSE MATERIAL

1 Answer the following questions.

a What is meant by the 'half-life of a radioactive substance'?
b What types of particle radiation are emitted by radioactive substances?
c What type of radiation from a source outside your body is the most dangerous and why?
d What is the difference between irradiation and (radioactive) contamination?

2 Radioactive marker substances are used in medical research to create images of the body.

a A radioactive marker substance is also known as a ....
b The radiation emitted by this type of marker substance is ....
c Why are other types of radiation not suitable for this kind of research?
d Why are artificial radioactive substances with short half-lives used for this type of examination?

IN PRACTICE

3 The amount of radiation emitted by a radioactive source keeps decreasing steadily.

a Calculate the missing data and use it to complete table 1.
b There is less than 1% of the original amount of radioactivity left after ...... half-lives.

table 1 This is how the radiation decreases.

number of half-lives	amount of radiation remaining
0	100%
1	50%
2	25%
3	
4	
5	
6	

4 Esther puts four radioactive sources in front of small sheets of different materials (figure 11). The thickness of the arrows is a measure of the amount of radiation. She knows that one source emits alpha radiation only, one emits beta radiation only, one emits gamma radiation only and one emits alpha and gamma radiation.
For each of the sources, state what type (or types) of radiation is being emitted and explain your answer.

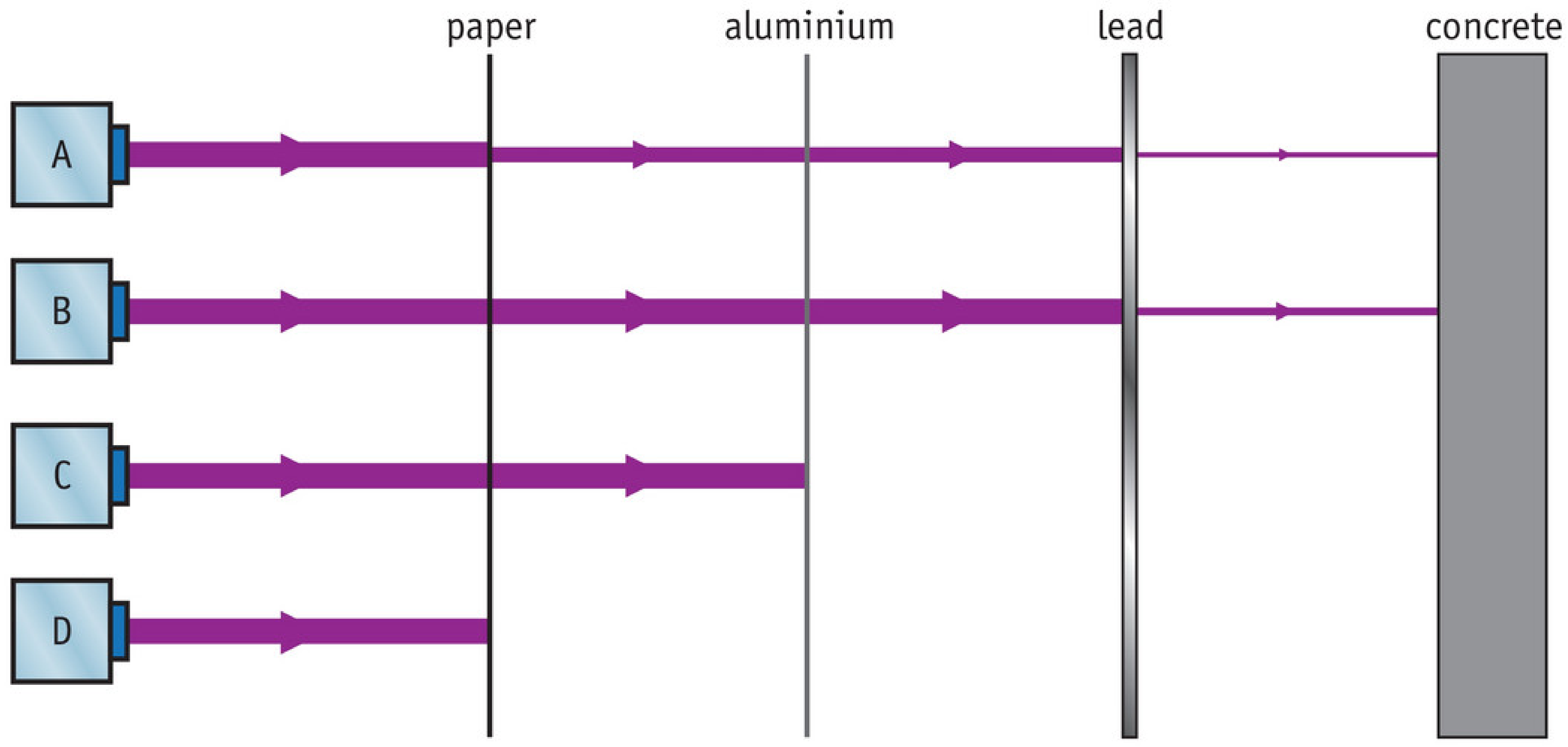


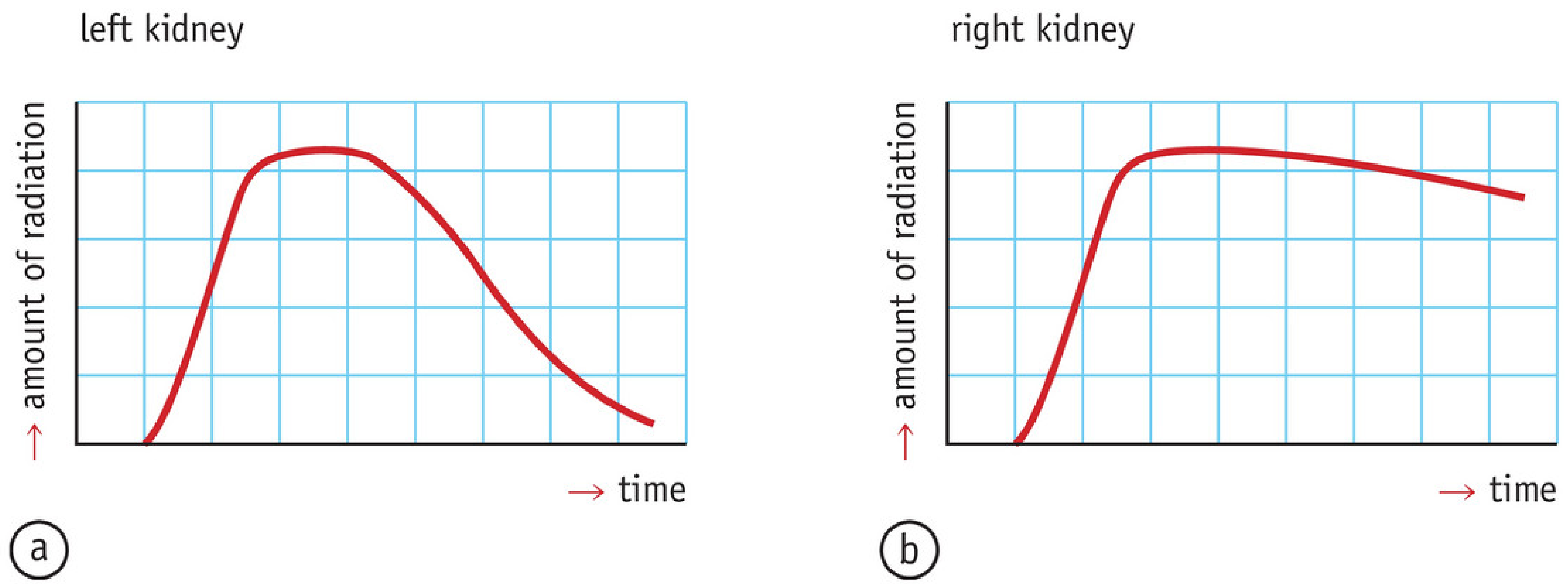
figure 11 Esther's experiment with four radioactive sources.

5 The way your kidneys work can be examined using a radioactive tracer. The tracer is placed in the bloodstream by an injection. If the kidneys are working well, they will filter the tracer from the blood quickly and carry it to the bladder.

a Two detectors measure the amount of radiation that the kidneys emit. Figure 12 shows you how the level of radiation changes with time.
Which kidney is working well and which is not? Explain how you can see that.

b The radioactive substance used has a half-life of 6 hours.
Explain why 6 hours is a good value for this examination.

figure 12 The amount of radiation as a function of the time.



6 Lead is often used for protection against gamma radiation.

a Use figure 13 to calculate how thick the lead shielding must be:

- to absorb 50% of the gamma radiation falling on the body: .... mm
- to absorb 90% of the gamma radiation falling on the body: .... mm

b A container holds a radioactive source that emits gamma radiation. The container has lead walls that are 4.5 cm thick.
Determine the percentage of the gamma radiation that is blocked by the container.

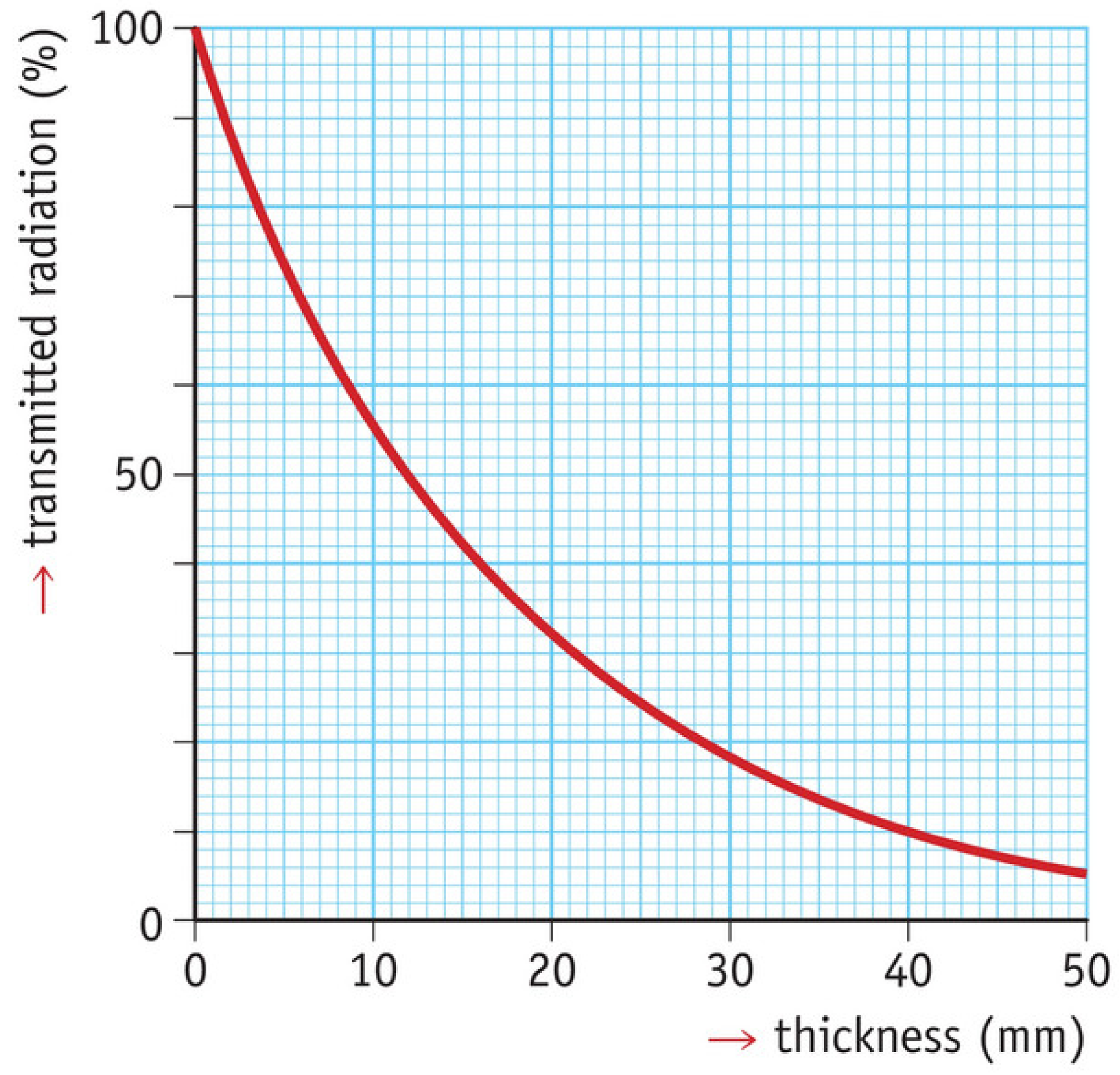


figure 13 The thicker the layer of lead, the less gamma radiation can pass through it.

7 After being treated in the hospital, the patient's urine may be radioactive. The urine therefore has to be collected and treated as radioactive waste.
Explain whether this precaution is needed:

a for patients who have been externally irradiated;
b for patients who have been internally irradiated.

8 The safety rules for working with radiation sources are based on four principles: keeping well away, using them for short periods, good protection and prevention of contamination.
For each line in figure 14, write down which principle it is based on.

1. Do all actions quickly but accurately.
2. Only take the amounts that are needed and leave the rest in the stock room.
3. Do not pick up the radiation source with your hands.
4. Wear a lead apron when working with radioactive substances (see photo).



figure 14 Safety rules for handling radioactive sources.

9 Irradiation of food is a technique for increasing the shelf life. Bacteria, moulds, insects and many other parasites are killed by irradiating the food. Irradiating food also slows down the ripening process and prevents vegetables from sprouting so quickly.

a Do the products become radioactive from the irradiation?
b Why are gamma rays used for this irradiation?
c Why do vegetables sprout less quickly if they have been irradiated?
d Many people say they would definitely not want to buy irradiated food products. Do you think they are right? Why (or why not)?

Test what you know with *Test yourself*.

PLUS RADIOTHERAPY

10 Figure 15 shows you how a tumour is irradiated. During the treatment, a cobalt-60 source is rotated around the patient's body.

a What kind of radiation must cobalt-60 emit (at least)? Explain your answer.
b Explain why the source moves around the patient in a circle.
c The source is enclosed in a lead housing with just one opening. Explain what this opening is used for and where it therefore has to be.

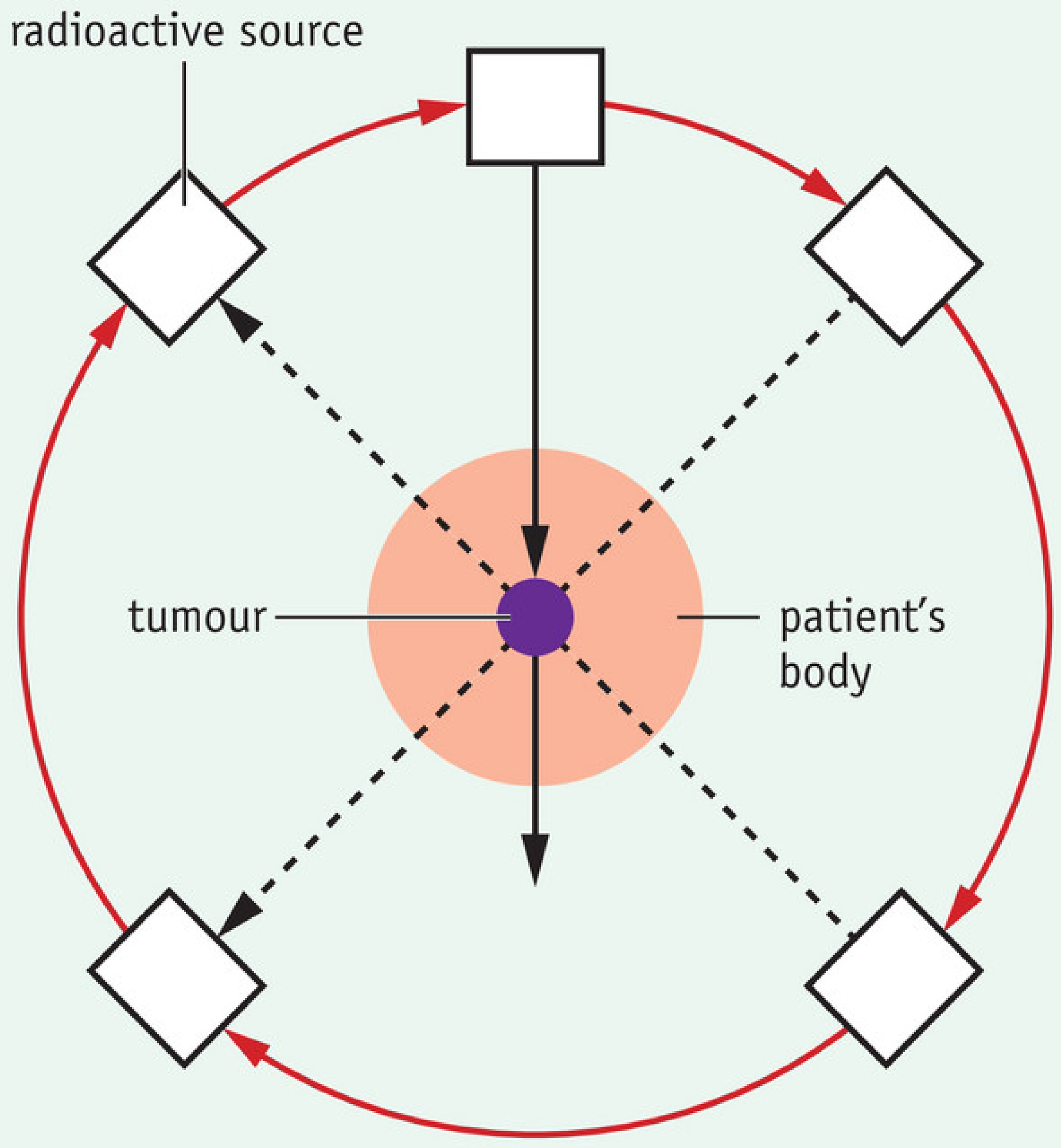


figure 15 A radioactive source is rotated around a patient.

11
a Explain whether external irradiation involves just irradiation or contamination.
b Explain whether internal irradiation involves just irradiation or contamination.
c Explain why a patient who is receiving internal irradiation may not have visitors during the treatment.

12 Various radiation sources are used for internal irradiation. Table 2 shows you what kind of radiation these sources emit and their half-lives.

a Explain why ruthenium-106 is suitable for internal irradiation but not for external irradiation.
b Iodine-131 is used for treating people whose thyroid is overactive. The patient is given a radioactive drink containing iodine-131, a substance that attaches in particular to active thyroid cells. These cells get damaged and die off, returning the level of thyroid activity to normal.
Write down one benefit and one drawback of the short half-life of iodine-131.

table 2 Type of radiation and half-life of radiation sources that are used for internal irradiation.

radiation source	type of radiation	half-life
caesium-137	γ-radiation	30.17 years
cobalt-60	γ-radiation	5.26 years
iridium-192	γ-radiation	74.0 days
iodine-125	X-rays	59.6 days
palladium-103	X-rays	17.0 days
ruthenium-106	β-radiation	1.02 years
iodine-131	β-radiation	8.0 days

Experiments

EXPERIMENT 1 FINDING THE FOCAL POINT

30 minutes

Introduction

If a parallel beam of light is perpendicular to a lens, the light will be refracted towards one point, the focal point F. The distance from the centre of the lens to the focal point F is called the focal length, *f*.

Aim

The question you are studying is:
Does the focal length as measured match the value stated by the manufacturer?

Requirements

- ☐ light box
- ☐ several positive cylindrical lenses
- ☐ a negative cylindrical lens
- ☐ sheet of white paper

Doing the experiment and writing it up

- Slide the light within the light box so that a parallel beam of light falls on the paper. The beam of light must be narrower than the smallest lens. Check that the beam of light is really parallel.
- Put a positive lens on the sheet of paper in the parallel beam of light (figure 1). Place a letter F on the paper to show where the focal point is.
- Mark the position of the lens. Turn the lens around. Does this change the position of the focal point?
- Measure the focal length of each lens.
- Put a negative lens in the beam of light. Think how you could then measure the focal length.

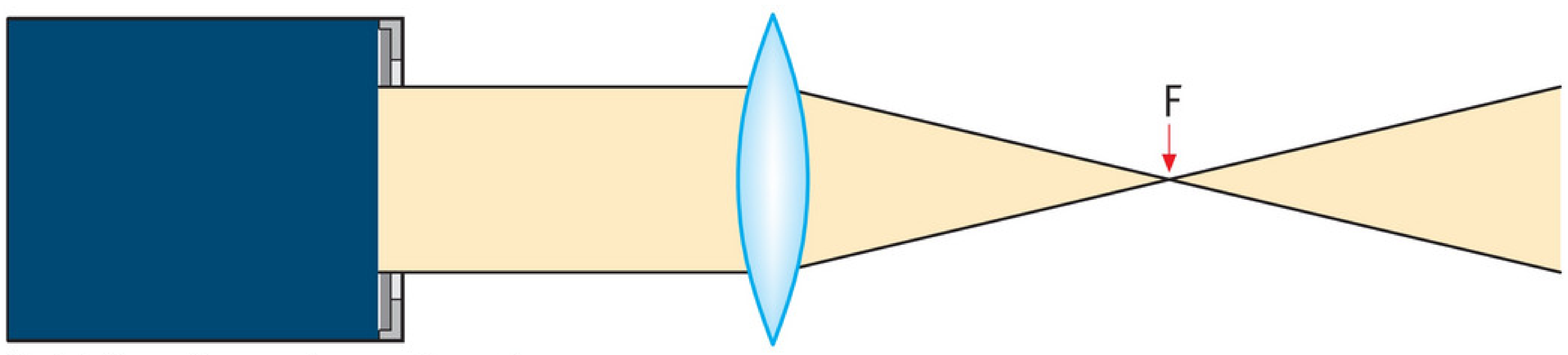


figure 1 How to place a lens in the parallel beam of light.

1 Arrange the lenses in order of strength, with the least powerful lens first.

....

....

....

2 Could you have predicted beforehand which lens would be the strongest?

....

....

....

3 Answer the study question.

....

....

....

....

EXPERIMENT 2 MAKING AN IMAGE WITH A CONVEX LENS

20 minutes

Introduction

You can use a positive lens to create an image of an object on a screen. When the picture is sharp, all the light coming from any single point on the object and passing through the lens comes together at a single point on the screen.

Aim

The question you are studying is:
How does a positive lens make an image on a screen?

Requirements

- ☐ positive lens (f = 10 cm)
- ☐ lens holder
- ☐ screen
- ☐ a block with two bulbs on
- ☐ voltage source
- ☐ two wires
- ☐ ruler

Doing the experiment and writing it up

- Set the experiment up as shown in figure 2.
- Put the lens 15 cm from the bulbs.
- Put the screen 5 cm behind the lens.

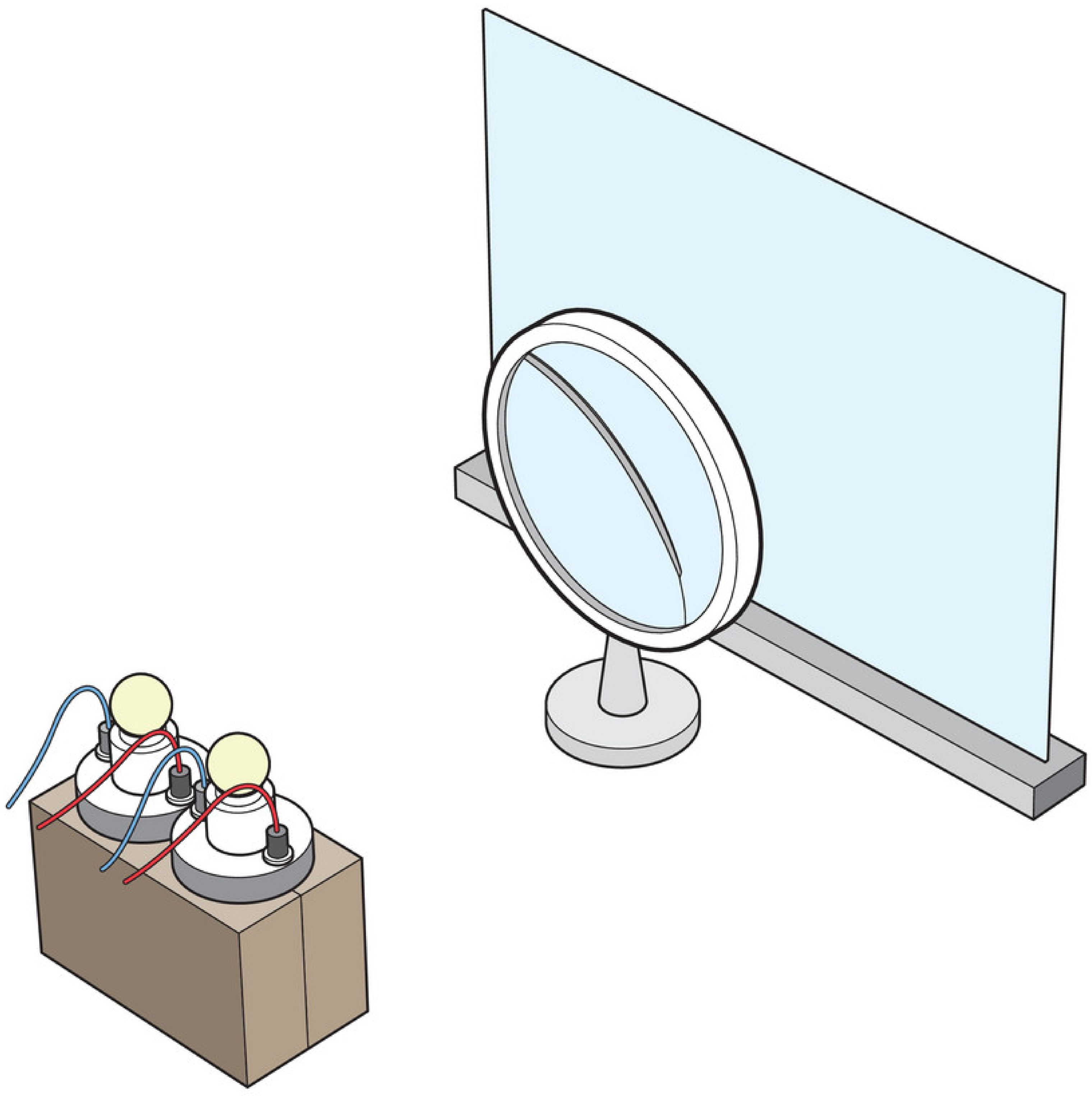


figure 2 The setup for Experiment 2.

1 Measure the diameter of one of the spots of light on the screen.

....

- Move the screen 5 cm further away from the lens.

2 Are the spots of light getting larger or smaller?

....

3 Are the rays in the beam converging (coming together) or diverging (moving apart) at the screen?

....

- Slide the screen further backwards until the spots are as small as possible. You will then see a clear image of the two bulbs.

4 Are the bulbs shown the right way up or upside down?

....

- Cover the left-hand bulb with your hand.

5 Does the right-hand bulb or the left-hand one disappear from the image?

....

- Hold one bulb above the other. Cover the upper bulb with your hand.

6 Does the top bulb or the bottom one disappear from the image?

....

- Move the screen another 10 cm away from the lens. Look at the spots of light that you see on the screen now.

7 Are the rays in the beams converging or diverging here?

....

8 Read your answers to questions 1 to 7 again.

a Describe how the spots of light change as you move the screen further and further away from the lens.

....

....

....

....

....

b Explain why the spots of light change in that way. Tip: add a sketch with your explanation.

....

....

....

....

....

....

....

....

c Use a drawing to explain how you can interpret the results of Exercises 5 and 6.

d The lens is creating a sharp image. You then replace the lens with a stronger one. What direction will you then have to move the screen in to get a sharp image again?

....

....

....

9 Answer the study question.

....

....

....

EXPERIMENT 3 PRODUCING A DESIGN – THE CAMERA OBSCURA

60 minutes

Introduction
A camera obscura is the precursor of the photo camera with a lens.

Aim
You are going to make your own camera obscura.

Doing the experiment and writing it up
- Find out what a camera obscura is.
- Search for a simple blueprint and present it to your teacher.
- Construct the 'camera' and test it.
- Compare the quality of your 'camera' with what the other groups have made.

Tips
- The casing of the camera obscura must not let any light through.
- Make sure that you are in the dark too when testing it. You can put a towel over your head, for example.

The following experiments can be found in the online learning environment. Your teacher decides which of these experiments will be done.

EXPERIMENT 4 THE LENS EQUATION

45 minutes

Introduction
You are investigating the relationship between the focal length, the object distance and the image distance.

EXPERIMENT 5 AN INVESTIGATION INTO THE REFRACTIVE INDEX

80 minutes

Introduction
You will be determining the refractive indices of liquids.

EXPERIMENT 6 PRODUCING A DESIGN – THE TELESCOPE

90 minutes

Introduction
You are designing a telescope.



The art of unmasking

It is the nightmare of every art collector: paying a six-figure sum for a painting from the Dutch Golden Age and having to hear later on, "I'm so sorry Sir, Madam, we have examined it and unfortunately there is no doubt: your painting cannot possibly be from the seventeenth century. The canvas is antique, but the paint is recent, not even forty years old. It seems you have been cheated..."

Art lovers are not the only ones who are cheated. It also happens to real professionals A few years ago, there was a commotion in Belgium about a *Madonna and Child* by – or so everyone thought – the old master Rogier van der Weyden (1399–1464). The painting had been at the Museum of Fine Arts in Tournai for fifty years and experts said it was a masterpiece. Everyone was therefore very much surprised when the truth came to light. An investigation showed that the *Madonna and Child* was the work of a twentieth-century forger. "Nothing on the canvas is from the fifteenth century," says Roger van Schoute, one of the experts.

And yet the painting looks totally authentic, even down to the *craquelure* (the small cracks in the paint).

HIDDEN LAYERS

Art experts will not readily admit it, but a really good forgery cannot be identified with the naked eye. That is why collectors and museum directors are relying more and more often on scientific investigations. Paintings can be examined in various ways: not only with visible light, but also with infrared, ultraviolet and X -rays. Each form of radiation shows details that otherwise cannot be seen.

"Art experts won't readily admit it, but a really good forgery cannot be identified with the naked eye."

An oil painting has a complex structure with various layers of different thicknesses. The bottom layer is the support: stretched canvas or a wooden panel. The painter would have covered it with a gouache filler layer first. After that, he made a charcoal drawing of the composition that he had thought up.

Only then would he start painting with oil paints. First an underpainting with relatively little colour, and thin semi-transparent layers of paint after that. That slowly resulted in a painting with deep and lifelike colours. Finally, the painting was given a transparent varnish as protection against dust and dirt.

SCREENING A PAINTING

There are different techniques for studying each layer (figure 1). The varnish layer can be checked with UV. This will make the varnish light up, just like a banknote that lights up under a UV lamp. The varnish is converting the UV radiation into visible light when that happens. Natural varnishes from earlier times then emit a yellow-green light. Modern synthetic varnishes light up white or purple.

A researcher uses X-rays for the deeper-lying layers of paint. Each layer of paint consists of granules of pigment (the coloured dye) in a binding agent such as linseed oil. Pigments containing heavy metals used to play an important role in the art of painting (figure 2). The old masters used compounds such as white lead, lead-tin yellow and vermillion (a red compound of mercury and sulphur). These pigments are highly toxic. They are not used any longer or are hardly used now, but once they could be found in every artist's studio.

The majority of pigments let X-rays pass through, but ones containing heavy metals such as lead or mercury don't. Because they absorb X-rays, they are clearly visible on X-ray photographs.

White lead was an important component of the underpainting, the first basic version of an oil painting that was used as the foundation for the later layers. The absorbent white lead means that underpainting like that can be seen clearly on an X-ray photo. In general, the underpainting should be the same as the painting you see. If the underpainting looks very different, this is an indication for fraud.



figure 2 Pigments containing heavy metals.

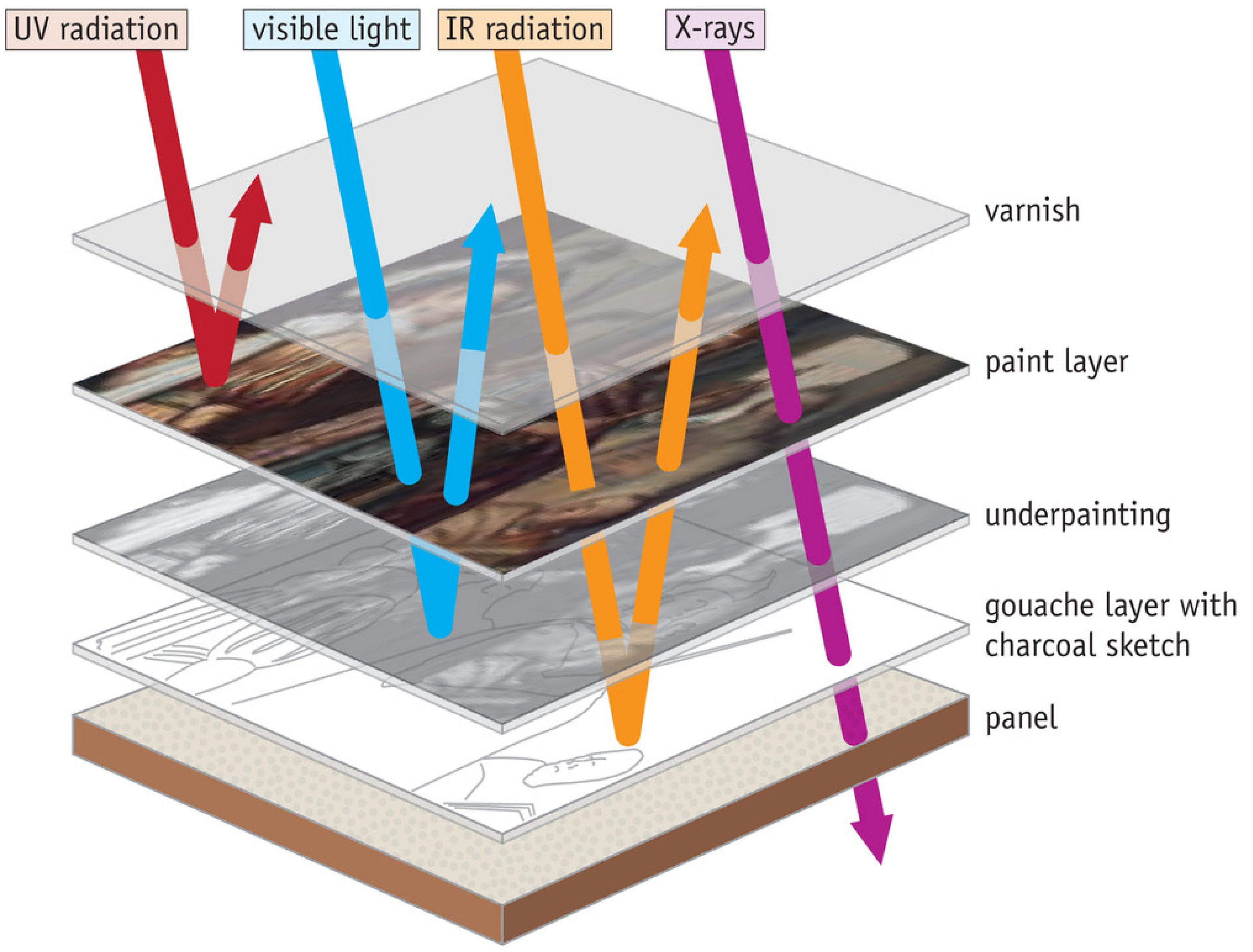


figure 1 Different types of radiation are used for studying the various layers of paint.



figure 3 You can see the charcoal sketch on this painting.

REFLECTIONS IN INFRARED

The painter then used charcoal to draw a sketch onto the gouache layer (figure 3). Charcoal is made of carbon, which X-rays can pass straight through. X-rays cannot therefore be used to make an image of that drawing. IR radiation can, though.

The IR radiation passes through the layers of paint on the painting, after which it is reflected by the gouache layer and then passed back outside again. This reflection is different at points where charcoal has been used. Charcoal is black and it absorbs the IR radiation. The charcoal lines of the drawing therefore only reflect the IR radiation slightly or not at all (figure 4). An infrared camera captures the reflected radiation and converts it into a black and white image. It shows the charcoal drawing surprisingly clearly. The researchers then investigate whether that sketch is by the Old Master himself. If so, it is highly probable that the painting is an original work. If not, the painting has probably been made by someone else.

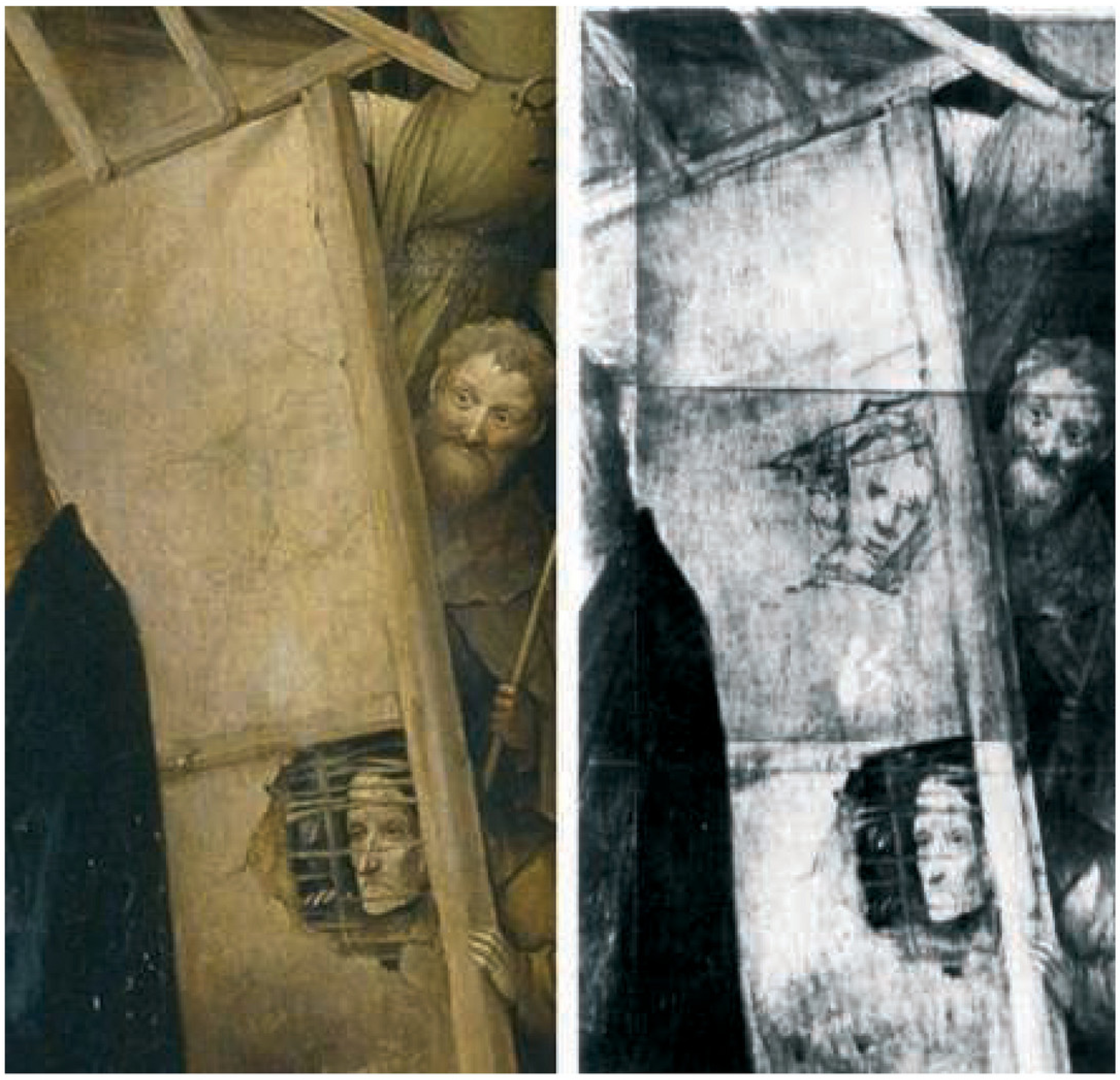


figure 4 IR radiation reveals the charcoal lines of the underlying sketch.

CARBON-14 DATING

Paintings always contain natural materials, such as the canvas or the wood panel that is painted on. These materials are plant-based and so you can date them using the carbon-14 method (see inset text). You can calculate the age of the materials fairly accurately by looking at the amount of radioactive carbon-14 left in these materials.

If the carbon-14 method gives an age that is much too young, then you know that the painting must be a forgery. This is not necessarily the case for the reverse. A forger can buy an old but worthless painting and simply paint his forgery over it. Additional studies are always needed in addition to carbon-dating to be sure if the painting is real.
That additional study is the key. If a painting is a forgery, there are always things that are not right. But you never know beforehand what you have to look for. You have to learn to keep on searching patiently until you find the one mistake that unmasks the fraud.

The carbon-14 method

Cosmic radiation from the universe is generating new carbon-14 in the atmosphere at a steady rate all the time. As a result, the ratio in the atmosphere of stable carbon-12 to radioactive carbon-14 remains more or less constant.
Throughout its entire life, a plant absorbs carbon from the atmosphere. That is why both isotopes are found in the plant, in the same ratio as in the atmosphere. That changes when the plant is harvested: a dead plant does not absorb carbon-14 anymore.
The amount of carbon-14 in it will become less and less because of natural decay. Investigators can calculate the age of the material by measuring the ratio between the remaining carbon-14 and carbon-12.

EXERCISES

1

The varnish on a painting will start to fluoresce when UV radiation lands on it. The varnish emits radiation then too.

- **a** What limits is the wavelength of the emitted radiation between? How can you tell?
- **b** Explain why it is not wise to expose a painting to strong UV radiation for a long time.

2

X-ray photos are often used when old paintings are being investigated. The painting is put down flat for this purpose with the X-ray source a little above it and the radiation detector below it.

- **a** Does it make any difference whether the researcher lays the painting face up or face down?
- **b** Why is the underpainting clearly visible on an X-ray photo, whereas the layers of paint on top of it are almost invisible?
- **c** Can you see what layer a certain pigment has been used in on an X-ray photo? Explain why or why not.

3

Search the Internet for a *carbon dating calculator*.

- **a** The canvas of a painting still contains 95% of the original amount of carbon-14. So how old is the canvas?
- **b** A well-known painting by the Italian painter Giotto was painted on a wooden panel around 1310.
  The remaining percentage of the original amount of carbon-14 in the wood is now at most ……………………%.
- **c** Explain why the phrase ‘at most’ was used in Exercise (b).

Course material overview

6.1 ELECTROMAGNETIC RADIATION

REMEMBER

- Electromagnetic waves are produced by antenna because the electrons in it move up and down very quickly. In a receiving antenna, the electromagnetic waves then make the electrons move.
- Electromagnetic waves move away from the source in all directions. They propagate independently without a medium, even through a vacuum.
- Electromagnetic waves always have the same speed in a vacuum: $3.0 \cdot 10^8$ m/s. This speed is called the speed of light and it has its own symbol, *c*.
- If you know the frequency of an electromagnetic wave, you can calculate the wavelength using the formula $\lambda = \frac{c}{f}$
- Every type of electromagnetic radiation is characterised by the frequency and its corresponding wavelength. The following six types of electromagnetic radiation can be distinguished, in decreasing order of wavelength: radio waves, IR radiation, light, UV radiation, X-rays and gamma rays.
- UV, X-rays and gamma rays are ionising radiation. They can break molecules apart. Radio waves, IR radiation and light cannot do that.

CONCEPTS

electromagnetic waves
High-frequency waves that are produced by alternating currents. They make it possible to transmit information through the air, as is done for example by mobile phones.

frequency
The number of wave peaks passing per second.

ionising radiation
Radiation that can break molecules apart.

spectrum
An overview in which various types of electromagnetic radiation are ordered by frequency.

speed of light
The speed of light in a vacuum is 299,792,458 (or $3.0 \cdot 10^8$) metres per second.

wavelength
The distance between two successive wave peaks or troughs.

6.2 LIGHT AND LENSES

REMEMBER

- A positive or convex lens is thicker in the middle than at the edges. Rays of light that run parallel to the axis in front of the lens are deflected to the focal point.
- The object distance *o* is the distance between the lens and the object; the image distance *i* is the distance between the lens and the image.
- You use two construction rays for constructing the image distance: construction ray 1 goes through the centre of the lens and does not change direction; construction ray 2 runs parallel to the main axis in front of the lens and goes through the focal point F of the lens beyond the lens.

CONCEPTS

constructing
Using a scale drawing to determine where a sharp image will be produced behind the lens.

construction rays
Two lines that you can use to find out where an image is behind the lens. These lines represent rays.

convex lens
A lens that is thinner at the edges than in the middle.

focal length
The distance between the centre of the lens and the focal point.

focal point
Rays of light that run parallel to the axis in front of a lens are deflected to converge at this point.

image distance
Distance between the lens and a sharp image of an object.

image point
A point on the optical image. In a digital camera, this corresponds to a pixel in the image.

main axis
The line that runs through the centre of the lens perpendicular to the lens.

object distance
The distance between the lens and the object.

positive lens
A convex lens – one that is thinner at the edges than in the middle.

refraction
The effect in which a ray of light changes direction when it falls on the boundary surface between transparent substances.

6.3 MAKING X-RAY PHOTOGRAPHS

REMEMBER

- When electromagnetic radiation falls on an object, it can:
  - pass through: transmission;
  - be reflected back: reflection;
  - be absorbed: absorption.
- To make an X-ray photograph, you need an X-ray source and a detector screen. On the X-ray, hard tissues such as bones and teeth are white and soft tissues are darker.
- Radiation that goes straight through your body does no harm. The energy of radiation that is absorbed is transferred to molecules in your body that can then be broken.
- Employees who work with X-ray equipment have to be properly protected. They can do this by keeping far enough out of the way or by standing behind a wall with lead in.

CONCEPTS

absorption
When radiation is taken up by an object or substance (neither reflected nor transmitted).

detector screen
A plate with detectors that are sensitive to e.g. X-rays.

equivalent dose
A measure for the biological damage that is caused when the body absorbs radiant energy.

reflection
When radiation bounces back off a surface.

transmission
When radiation passes through an object or substance.

X-ray source
A device that produces X-rays.

6.4 WORKING WITH GAMMA RADIATION

REMEMBER

- A radioactive substance is one that emits strongly ionising radiation.
- The half-life shows how long it takes before half of a radioactive substance is converted into another substance.
- Radioactive substances can emit both particles and electromagnetic radiation. Alpha and beta radiation are both particle radiation; gamma radiation is electromagnetic radiation. Gamma radiation has the greatest penetrating power, followed by beta radiation and then alpha radiation, which has the least penetrating power.
- Tracers or radioactive markers are used for making scans of your body. They emit gamma radiation that is detected by a gamma camera outside the body. A computer uses this data to construct an image.
- Your body is said to be being irradiated if the radiation from a source passes through your body. If radioactive substances end up on or inside your body, this is called contamination. Irradiation does not make your body radioactive.

CONCEPTS

alpha radiation
The type of radiation that occurs in alpha decay. This type of radiation does not have much penetrating power.

artificially radioactive
Substances that are artificially radioactive are synthesised (by people).

beta radiation
The type of radiation that occurs in beta decay. This type of radiation has greater penetrating power than alpha radiation, but less than gamma radiation.

gamma camera
A camera that creates images based on gamma radiation.

gamma radiation
The type of radiation that occurs in gamma decay. This radiation consists of waves that propagate at the speed of light and have high penetrating power.

half-life
The property of an isotope that states the time it takes for half the unstable atomic nuclei to decay, thereby indicating how long it takes for the activity of the source to halve.

naturally radioactive
Substances that are naturally radioactive occur in nature.

particle radiation
A stream of very tiny particles that move in all directions very quickly.

penetrating power
The ability of a type of radiation to get deep inside a substance.

penetration depth
The maximum distances that alpha and beta particles can travel in a substance.

radioactive
A term for a substance that emits strongly ionising radiation.

radioactive contamination
The situation in which radioactive substances end up in or on the body so that the body is not only damaged but also becomes a radioactive source itself.

scan
An image of the human body that is made by passing radiation through the body in various directions.

tracer
A radioactive marker substance. It can be used for doing research into the way specific organs work. It can also be used for tracing tumours.

Go to the *Flash cards* and the *Diagnostic test*.

Skills

GATHERING AND PROCESSING DATA

Physics is often about both knowledge (what you know) and skills (what you can do). The skills include aspects such as building experimental setups, collecting the measurement data, performing calculations and drawing graphs. This part of the book gives you a summary.

1 Doing research 179
2 Working with variables and units 180
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6 Rewriting formulae 186
7 Rounding off results 187
8 Working with tables and graphs 189
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10 Writing a report 192



1 Doing research

Research starts with a question that you are studying. You make a plan to find the answer, and then you carry out that plan yourself. You do this step by step.

Step 1 **Think of a study question.**
Sometimes this will already be stated in the exercise. In that case, all you have to think about is how you can answer the question. Sometimes you are expected to think up a study question of your own. Don't be content with it too quickly: you must have some idea of how you could answer your question. Formulate your study question as precisely as possible before you go any further.

Step 2 **Make a working plan.**
In your working plan, you should write down:

- what variables you are going to measure;
- what materials and equipment you will need;
- what experimental setup you are going to construct (make a drawing);
- what measurements you are going to make;
- which formulae you are going to use (if applicable).

Step 3 **Doing the experiment and writing it up.**
You construct the experimental setup and use it for carrying out the measurements as planned. After each measurement, you make a clear note of the measured values, for example in a table. After you have finished, you work out the measurements in more detail, for instance by drawing a graph or doing calculations. If necessary, use the other skills for this too.

Step 4 **Drawing conclusions.**
If everything has gone as intended, you are now able to draw your conclusions. Taken together, the conclusions provide the answer to the study question. A conclusion is not a summary of the measurement results: it is something that you can derive (conclude) from the measurements. You should also think about what you could have done better in your research.

Step 5 **Writing a report.**
Finally, you make a report of your research. See the skills section on '*Writing a report*'.

2 Working with variables and units

A variable is something that you can measure. Example of variables are mass, force, resistance and time. To be able to measure a variable, you need units to express it in. You measure mass in kilograms, force in newtons, resistance in ohms and time in seconds.

The size of a unit is often not convenient for the variable you want to measure. In that case, you can put a multiplier prefix before the unit. Instead of saying that the thickness is 0.0003 metres, you would write "The thickness is 0.3 mm."

You can always replace these prefixes with a power of ten (and vice versa). Instead of saying that insulating the pipes would save 4.8 GJ of heat, you could also write "Insulating the pipes saves you $4.8 \cdot 10^9$ J of heat." See table 1.

table 1 Prefixes and their meanings.

prefix	abbreviation	meaning	example
giga	G	10^9	1 GJ = 10^9 J
mega	M	10^6	1 MW = 10^6 W
kilo	k	10^3	1 kN = 1000 N
hecto	h	10^2	1 hPa = 100 Pa
deca	da	10^1	1 dam = 10 m
deci	d	10^{-1}	1 dL = 0.1 L
centi	c	10^{-2}	1 cm = 0.01 m
milli	m	10^{-3}	1 mΩ = 0.001 Ω
micro	µ	10^{-6}	1 µg = 10^{-6} g
nano	n	10^{-9}	1 ns = 10^{-9} s

Sometimes there are several units that are in use for the same variable. Think of electrical energy, which can be in joules (J) or kilowatt-hours (kWh), or a speed in metres per second (m/s) or kilometres per hour (km/h). In that case, you sometimes have to convert a value from one set of units to another.

EXAMPLE EXERCISE 1

According to a consumer organization, an average family in the Netherlands uses about 300 kWh of electrical energy per year.
What is that in joules?

1 kWh = $3.6 \cdot 10^6$ J

300 kWh = $300 \times 3.6 \cdot 10^6 = 1.08 \cdot 10^9$ J (or 1.08 GJ)

EXAMPLE EXERCISE 2

A car manufacturer states that the top speed of its high-performance model is 255 km/h.
What is that in m/s?

1 m/s = 3.6 km/h

255 km/h $= \dfrac{255}{3.6} = 71$ m/s

3 Working with powers of ten

In physics, you often have to deal with numbers that are extremely large or extremely small. There is a handy way of writing numbers like those. For large numbers, you use positive powers of 10. For small numbers, you use negative powers of 10.

positive powers	**negative powers**
$10^1 = 10$	$10^{-1} = 1/10 = 0.1$
$10^2 = 10 \times 10 = 100$	$10^{-2} = 1/10 \times 1/10 = 1/100 = 0.01$
$10^3 = 10 \times 10 \times 10 = 1000$	$10^{-3} = 1/10 \times 1/10 \times 1/10 = 1/1000 = 0.001$
etc.	etc.

If you want, you can replace the power of 10 with a prefix. Instead of saying that Instead of writing “The capacity of the power plant is $4.75 \cdot 10^8$ W”, you can also write “The capacity of the power plant is 475 MW.” Work it out:
$4.75 \cdot 10^8$ W = $475 \cdot 10^6$ W = 475 MW (M = 10^6)

EXAMPLE EXERCISE

The nuclear power plant in Gravelines (in France) has an electrical output of 5460 MW. In practice, only 75% of this capacity is actually delivered. On average, 25% of the capacity is not available, mostly because of maintenance.
Calculate how many kWh of electricity the nuclear power station produces in one year.

75% of 5460 MW = 4095 MW
P = 4095 MW = $4095 \cdot 10^6$ W = $4095 \cdot 10^3$ kW
$t = 365 \times 24 = 8760$ hours

$$
\begin{aligned}
E &= P \cdot t \\
&= 4095 \cdot 10^3 \times 8760 \\
&= 36 \cdot 10^9 \text{ kWh}
\end{aligned}
$$

The power station produces 36 billion kilowatt-hours of electrical energy every year.

table 2 Examples of powers of 10 from nature.

	height (m)	mass (kg)	time (s)
10^{-10}	diameter of an atom		
10^{-9}			
10^{-8}	diameter of the smallest virus		
10^{-7}		mass of a sand grain	
10^{-6}	diameter of a bacterium	mass of a raindrop	
10^{-5}	diameter of a red blood cell		
10^{-4}	thickness of paper	mass of a fly	duration of a lightning flash
10^{-3}			
10^{-2}	thickness of a finger	mass of a mouse	
10^{-1}			reaction time of a human
10^{0}	height of a human	mass of a bag of sugar	time between two heartbeats
10^{1}			world record for the 100 m sprint
10^{2}	length of a supertanker	mass of a human	
10^{3}		mass of a car	a quarter of an hour
10^{4}	maximum depth of the oceans		
10^{5}		mass of a jumbo jet	one day
10^{6}	diameter of the moon		
10^{7}	diameter of the earth		one year
10^{8}	Earth-Moon distance	mass of a supertanker	
10^{9}			lifespan of a human
10^{10}			
10^{11}	distance from the Earth to the Sun		age of the pyramids
10^{12}			modern humans present on Earth

4 Working with measuring instruments

You use all kinds of measuring instruments in physics. To measure things properly, you have to take it step by step.

Step 1 **Determine what measuring instruments you need.**
For an experiment, you will want to answer a question such as:
Is the electrical rating stated on this appliance correct?
You know that you can determine the electrical power (the rating) using the formula $P = U \cdot I$. That means that you have to measure the voltage (U) and the current (I). So you need two measuring instruments: a voltmeter and an ammeter.

Step 2 **Connect up the measuring instrument.**
Ammeters and voltmeters have to be connected up correctly: an ammeter in series with the device, a voltmeter in parallel (figure 1).
For direct currents and voltages, the direction the current is flowing in is also important. You have to connect the plus terminal of the meter to the positive terminal of the voltage source and the minus to the negative terminal. The plus terminal is usually a red jack socket and the minus is usually black (see figure 2).

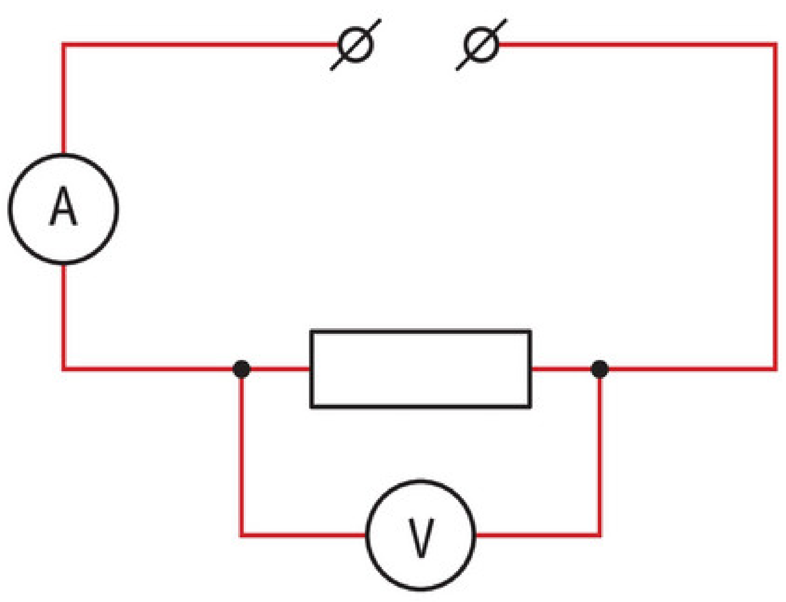


figure 1 How to connect up a voltmeter and ammeter.



figure 2 What is the current?

Step 3 **Select the correct measurement range.**
Ammeters and voltmeters often have more than one measurement range. The ammeter in figure 2, for instance, has three measurement ranges: 0 to 5 A, 0 to 0.5 A and 0 to 0.05 A. You can find out which measurement range you should be using as follows:

- Make a test measurement using the greatest measurement range.
- This lets you see roughly how big the current or voltage is.
- Then choose the smallest measurement range in which the meter can still be read.
- The smaller the measurement range you use, the more accurate the measurement result will be.

Step 4 **Read the measuring instrument.**

Many measurement instruments have a graduated scale. When you are taking a reading from a measuring instrument like this, you first have to determine how much each mark on the scale represents. Then you read the value off as accurately as possible.
In the ammeter in figure 2, for example, it goes like this:

- I have used the measurement range from 0 to 0.5 A.
- Between 0.3 and 0.4 A, there are ten gaps (nine other marks).
- Each mark is therefore equal to $\frac{0.1}{10}$ = 0.01 A.
- The needle is pointing to the sixth mark.
- The current is therefore 0.36 A.

5 Working with formulae

Physics often requires you to do calculations. You should take a step-by-step approach to this.

Step 1 **Read the exercise.**
Read the instructions and estimate roughly what the result should be. In the worked example, it asks you how long a kettle will take to boil one cup of water. You know that you will have to wait a few tens of seconds or a minute or so. If you get an answer of a couple of seconds, that is clearly too little. Similarly, five minutes is clearly too long.

Step 2 **Write down the data.**
Convert all the data into letter symbols and numbers, and make a note of it. A data item such as “44 kJ of heat” should for example be written as: $E = 44\ \text{kJ} = 4.4\cdot10^4\ \text{J}$.

Step 3 **Write the formulae down.**
Some formulae can be written in different ways. Use the form that has the variable you want to calculate in front of the equals sign. So you write:

- $E = P \cdot t$ if you want to work out the amount of energy (E);
- $P = \frac{E}{t}$ if you want to calculate the power (P);
- $t = \frac{E}{P}$ if you want to calculate the time required (t).

Step 4 **Fill in the data.**

Step 5 **Do the calculation.**

Step 6 **Write down the result.**
The result is a number followed by a unit. The unit must match the data. If you give the power in watts (W = J/s) and the time in seconds (s), you will get the amount of energy in joules (J). See also *Rounding off results* in the Skills section.

Step 7 **Check the result.**
Compare the result against the estimate that you made at the start. You should also check that you did not make any calculation errors or mistakes when copying the numbers down.

EXAMPLE EXERCISE
Boiling water for a cup of tea requires 44 kJ of heat.
How long does a kettle of 1800 W take to supply this amount of energy?

given $E = 44\ \text{kJ} = 4.4\cdot10^4\ \text{J}$
$P = 1800\ \text{W}$

required $t = ?$

working $t = \frac{E}{P} = \frac{4.4\cdot10^4}{1800} = 24\ \text{s}$

6 Rewriting formulae

You often use formulae in physics. A formula can be written in more than one way. Sometimes one form will be handier and sometimes another will be better. That does not mean that you have to remember all the different forms. If you remember just one form, you can quickly work out the others from it. This is known as 'rewriting' the formula.

There are two mathematical methods you can use for rewriting formulae: cross-multiplication and the balancing method. Taks this formula, for example: $v = \frac{s}{t}$

Suppose that you want to use this formula to calculate the time *t*. You can rewrite the formula like this:

Method 1: Cross-multiplication

To do this, you first express both sides as fractions: $v = \frac{s}{t} \rightarrow \frac{v}{1} = \frac{s}{t}$, because $\frac{v}{1} = v$

Cross-multiply by the variables underneath:

$\frac{v}{1} = \frac{s}{t} \rightarrow v \cdot t = s \cdot 1 \rightarrow v \cdot t = s$

Now divide both sides by v: $v \cdot t = s \rightarrow \frac{v \cdot t}{v} = \frac{s}{v}$

Simplify the result: $\frac{v \cdot t}{v} = \frac{s}{v} \rightarrow t = \frac{s}{v}$, because $\frac{v}{v} = 1$

Method 2: The balancing method

This involves always doing the same thing on both sides of the equals sign. The equals sign actually means that the same value is represented on both sides of it, for example $3 = 3$, or $\frac{6}{2} = \frac{3}{1}$ or $v = \frac{s}{t}$

You can multiply both sides by the same number. The values on either side of the equals sign will change, but they will still be equal to each other. For example: $\frac{6 \cdot a}{2} = \frac{3 \cdot a}{1} \rightarrow 3 \cdot a = 3 \cdot a$

The same is true when you divide both sides by the same number.

Now multiply both sides of $v = \frac{s}{t}$ by t: $v = \frac{s}{t} \rightarrow v \cdot t = \frac{s \cdot t}{t}$

Write $v \cdot t = \frac{s \cdot t}{t}$ as $v \cdot t = s$, because $\frac{t}{t} = 1$

Divide both side by v: $v \cdot t = s \rightarrow \frac{v \cdot t}{v} = \frac{s}{v}$

Write $\frac{v \cdot t}{v} = \frac{s}{v}$ as $t = \frac{s}{v}$, because $\frac{v}{v} = 1$

7 Rounding off results

The results of a calculation cannot be more accurate than the data that you used. This means that you often have to round off the results of a calculation. Otherwise, it gives the impression of being a very accurate result when it really is not.

In the example exercise, the voltage is 134 mV and the current is 1.9 mA. You can see that the voltage has been given to three significant figures and the current to two significant figures. This means that the current is a less accurate data item. You have to allow for that when rounding off.

You can use a simple rule of thumb for rounding off:

The result is given to the same number of significant figures as the least precise data item.

It will also be reckoned to be OK if the result has one more significant figure, though.

You must take special care with the zeroes when counting the number of significant figures:

- Zeroes at the start of a number do not matter when you are counting the number of significant figures: 25 cm has just as many significant figures as 0.25 m. The leading zero is only telling you about the magnitude of the number – it doesn't say anything about the precision. It is not a significant digit.
- Zeroes in the middle or at the end of the number do count towards the number of significant figures. If your height is given as 1.80 metres, the zero is making clear that your height was measured to an accuracy of 1 cm. So this zero is indeed saying something about the accuracy.
- Some more examples:
  - 2.0 has two significant figures, but 0.2 only has one significant figure;
  - 0.22 and 0.022 both have two significant figures;
  - 2.02 has three significant figures.

To round off correctly, you look to see the first digit that has to be dropped. If that is a 5 or more, you have to 'round up'. That means that the digit before it has to be increased by 1. If the digit you are dropping is 4 or less, you do not have to increase the digit before it.

If you have to give an answer to three figures:

- you round 2.345 to 2.35;
- you also round 2.354 to 2.35;
- you round 2.395 to 2.40;
- you also round 2.404 to 2.40;
- and so forth.

EXAMPLE EXERCISE

When there is a voltage of 134 mV across a resistor, the current through it is 1.9 mA. Calculate the resistance.

given U = 134 mV = 0.134 V
I = 1.9 mA = 0.0019 A

required R = ?

working $R = \frac{U}{I} = \frac{0.134}{0.0019} = 71\ \Omega$

Explanation
If you do the sum on a calculator, the answer you will get is 70.526316. The data item I = 1.9 mA has the fewest significant figures: two. You should therefore also give your answer to two significant figures. So you drop all the numbers after the 70. However, because the first digit that you are dropping is a 5, you have to increase the digit in front of it and the 0 becomes a 1. The correctly rounded result is therefore 71 Ω.

8 Working with tables and graphs

Many study questions are about the relationship between two variables. Take the following study question, for example:
What is the relationship between the extension of a spring and the force that is exerted upon it?
This question is about the relationship between the force and the extension.

To answer the question, you carry out a series of measurements. You hand weights on the spring, measuring how far it extends each time. You then note down the measurement results in a table. After completing the experiment, you show the measurement results from the table in a graph.

You make the graph as follows:

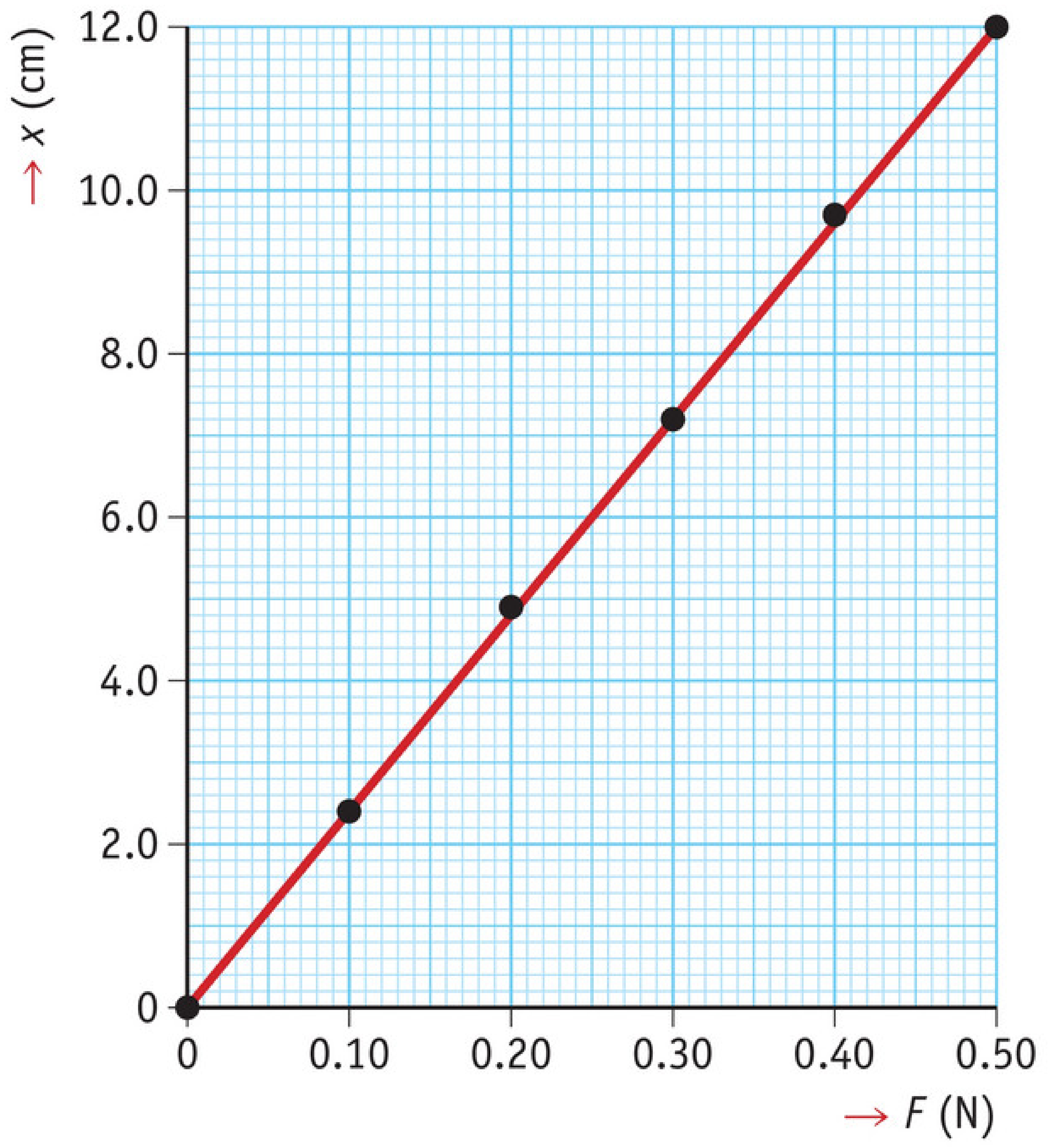


figure 3 A graph of extension against force.

Step 1 **Draw a set of axes.**

Step 2 **Label each axis with a variable and the corresponding units.**
For example, → F (N) and → x (cm).

Step 3 **Draw an appropriate scale along each of the axes.**
Make sure that the biggest numbers still fit on it.

Step 4 **Plot in the measurements as points.**

Step 5 **Draw in the lines.**
If all the points are on a straight line (or roughly on one), draw a straight line through them. If they are not, draw a smooth curve. Make sure that the line fits the points as well as possible, but never 'join the dots' one by one. It does not matter if the straight line or curve does not go precisely through all the measurement points.

9 Measuring relationships

Many study questions are about the relationship between two variables. Take the following study question, for example:
What is the relationship between the extension of a spring and the force that is exerted upon it?
In this question, the variables are the force (on the spring) and the extension (of the spring).

How can you measure this kind of relationship? A few hints:

Step 1 **First make a table that you can note the measurement results down in.**
Note the force on the left and the extension on the right.

Step 2 **Choose a step size for the variable in the left-hand column that is a convenient round number,**
for example the following values for the force (in N):
0.0 0.1 0.2 0.3 0.4 and so on.
That will make it easier to draw the graph later on.

Step 3 **Write the measured values down in the table: the force (in N) on the left and the extension (in cm) on the right.**

Step 4 **Make a graph using your measurements.**
The skills section on *Working with tables and graphs* tells you how to do that. Put the force along the horizontal axis and the extension on the vertical axis.

Step 5 **Compare your graph against figure 4.**

The figure shows you what your graph will look like:

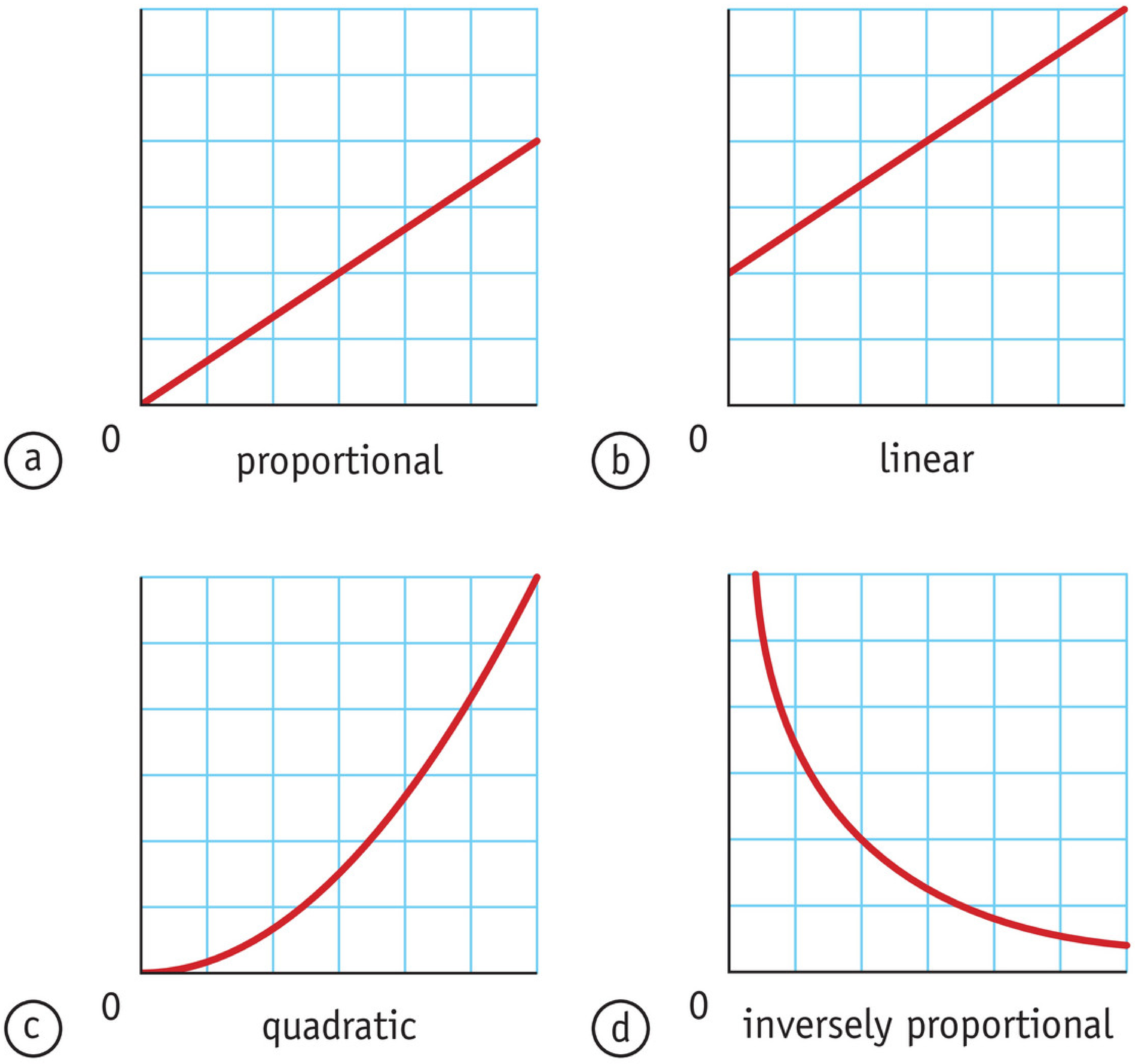
a if the relationship is proportional;

b if the relationship is linear;

c if the relationship is quadratic;

d if the relationship is inversely proportional.

figure 4 Four types of relationships.



The (x,F) diagram for a helical spring is a straight line through the origin (figure 3 in the skills section on *Working with tables and graphs*). This shows you that the relationship between the extension and the force is proportional for a helical spring.

10 Writing a report

Research has to be written up. In the report, you explain what happened during the experiment. Somebody who was not actually there must be able to understand exactly what happened.

Lay your report out like this:

Title page
This is where you can give the title of the report, the names of the pupils in your group doing the experiment, the name of your teacher and the date and year.

Section 1 Study question
This section is where you explain what question you want your study to answer.

Section 2 Working plan
This contains:
- what variable you have measured;
- the equipment you used for the experiment;
- the setup you made (make a sketch or photo);
- precisely what you did:
  - What measurements did you carry out?
  - How have you processed the measurements (drawings/calculations)?
  - What calculations did you do (including the formulas)?

Section 3 Experimental results
This is where you can state what you observed or measured. This can be in textual form or as tables, graphs, photographs and so forth.

Section 4 Conclusions
The answer to the study question can be stated here. You also say what could have been done better.

A report should look good. It is not only about the information that your report contains: You must also present the content clearly and neatly. A number of useful pointers:
- Use A4 size paper.
- Make sure there is plenty of space at the margins: top and bottom, left and right.
- Choose an easily readable font at a large enough size.
- Put a heading in bold above each section. Then skip a line.
- Make sure that the drawings, tables and graphs are neat. Add a number to each so that you can refer to them in the text.

Glossary

A

absorption absorptie
Opnemen van straling door een voorwerp of een hoeveelheid stof.

accelerating motion versnelde beweging
Een beweging waarvan de snelheid steeds groter wordt.

acceleration versnelling
De snelheidstoename per seconde.

acceleration due to gravity valversnelling
Versnelling (9,8 m/s^2) waarmee voorwerpen in vrije val naar de aarde vallen.

actuator actuator
Onderdeel van een schakeling dat de gewenste actie uitvoert.

alpha radiation alfastraling
Soort straling die ontstaat na alfaverval. Deze straling heeft een klein doordringend vermogen.

artificially radioactive kunstmatig radioactief
Stoffen die kunstmatig radioactief zijn worden kunstmatig (door mensen) gemaakt.

B

base basis
Een van de drie aansluitpunten van een transistor. De grootte van de stroom door de basis bepaalt of de collector stroom doorlaat.

beta radiation bètastraling
Soort straling die ontstaat na bètaverval. Deze straling heeft een groter doordringend vermogen dan alfastraling, maar minder dan gammastraling.

braking distance remweg
De afstand die een voertuig tijdens het remmen aflegt.

C

collector collector
Een van de drie aansluitpunten van een transistor. Of er stroom door de collector loopt, wordt bepaald door de grootte van de stroom die door de basis loopt.

constructing construeren
Met een tekening op schaal bepalen waar een scherp beeld achter de lens ontstaat.

construction rays constructiestralen
Twee lijnen die je kunt gebruiken om een beeld achter een lens te construeren. De lijnen stellen lichtstralen voor.

convex lens bolle lens
Lens die aan de rand dunner is dan in het midden.

crumple zone kreukelzone
Het gedeelte aan de voor- en achterkant van een auto dat zo is gemaakt dat het bij een botsing in elkaar schuift.

D

(displacement, time) diagram (plaats,tijd)-diagram
Een grafiek waarin de plaats is uitgezet tegen de tijd. Wordt ook (x,t)-diagram genoemd.

deceleration vertraging
De snelheidsafname per seconde.

detector screen detectorscherm
Een plaat met detectoren die gevoelig zijn voor röntgenstraling.

E

electrically charged elektrisch geladen
Situatie waarin een voorwerp een elektrische lading heeft.

electromagnetic waves elektromagnetische golven
Golven met een hoge frequentie die ontstaan als gevolg van een wisselstroom. Ze maken de overdracht van informatie mogelijk door de lucht, zoals bij mobiele telefoons.

electron elektron
Negatief geladen deeltje.

emitter emitter
Een van de drie aansluitpunten van een transistor.

equivalent dose equivalente dosis
Maat voor de biologische schade die ontstaat door de stralingsenergie die het lichaam absorbeert.

equivalent resistance vervangingsweerstand
Term voor de totale weerstand als meerdere weerstanden in serie of parallel geschakeld zijn.

F

focal length brandpuntsafstand
Afstand tussen het midden van de lens en het brandpunt.

focal point brandpunt
Lichtstralen die voor een lens evenwijdig aan de hoofdas lopen, komen na de lens samen in dit punt.

free fall vrije val
Een situatie waarbij op een voorwerp alleen de zwaartekracht werkt.

frequency frequentie
Het aantal golven dat per seconde voorbijkomt.

G

gamma camera gammacamera
Een camera die beelden maakt op basis van gammastraling.

gamma radiation gammastraling
Soort straling die ontstaat na gammaverval. Deze straling bestaat uit golven die zich voortplanten met de lichtsnelheid en heeft een groot doordringend vermogen.

H

half-life halveringstijd of halfwaardetijd
Eigenschap van een isotoop die aangeeft in hoeveel tijd de helft van de instabiele atoomkernen vervalt en die aangeeft na hoeveel tijd de activiteit van de bron met de helft is verminderd.

I

(I,U) diagram (I,U)-diagram
Grafiek waarin de stroomsterkte is uitgezet tegen de spanning.

image distance beeldafstand
Afstand tussen de lens en een scherp beeld van een voorwerp.

image point beeldpunt
Punt van een optisch beeld. In een camera is dit punt de weergave van het bijbehorende punt in de werkelijkheid.

inertia traagheid
De mate waarin een voorwerp van snelheid of richting kan veranderen. Voorwerpen met een grote massa hebben een grote traagheid en kunnen minder gemakkelijk van snelheid en richting veranderen.

ionising radiation ioniserende straling
Straling die moleculen kapot kan maken.

L

LDR LDR
Variabele weerstand die gevoelig is voor veranderingen in de hoeveelheid licht.

M

main axis hoofdas
Lijn die door het midden van de lens loopt, loodrecht op de lens.

N

naturally radioactive natuurlijk radioactief
Stoffen die natuurlijk radioactief zijn komen in de natuur voor.

negative charge negatieve lading
De lading die een (neutraal) voorwerp krijgt als het elektronen opneemt.

neutral neutraal
Situatie waarin een voorwerp evenveel positieve als negatieve lading bevat.

Newton's Second Law tweede wet van Newton
De formule $F = m \cdot a$

NTC NTC
Variabele weerstand die bij een lagere temperatuur een hogere weerstand krijgt.

O

object distance voorwerpsafstand
Afstand tussen de lens en het voorwerp.

Ohm's Law wet van Ohm
Regel die stelt: de spanning (over de draad) en de stroomsterkte (door de draad) zijn recht evenredig.

ohmic resistance ohmse weerstand
Een weerstand waarvan de weerstand bij elke spanning even groot is.

P

particle radiation deeltjesstraling
Stroom zeer kleine deeltjes die met grote snelheid verschillende richtingen op bewegen.

penetrating power doordringend vermogen
Het vermogen van een soort straling om in een stof door te dringen.

penetration depth dracht
De maximale afstand die alfa- en bètadeeltjes in een stof kunnen afleggen.

positive charge positieve lading
De lading die een (neutraal) voorwerp krijgt als het elektronen afstaat.

positive lens positieve lens
Bolle lens die aan de rand dunner is dan in het midden.

pressure druk
De kracht die een voorwerp op de ondergrond per oppervlakte-eenheid uitoefent.

proton proton
Positief geladen deeltje.

R

radioactive radioactief
Benaming van een stof die ioniserende straling uitzendt.

radioactive contamination radioactieve besmetting
Situatie waarbij radioactieve stoffen in een lichaam terechtkomen, waardoor het lichaam niet alleen wordt beschadigd, maar zelf een radioactieve bron wordt.

reaction distance reactie-afstand
De afstand die een voertuig tijdens de reactietijd aflegt.

reflection reflectie
Weerkaatsen van straling door een oppervlak.

refraction lichtbreking
Verschijnsel dat optreedt als een lichtstraal van richting verandert wanneer de straal op het grensvlak tussen twee doorzichtige stoffen valt.

resistance weerstand
De eigenschap van een component die bepaalt hoe gemakkelijk elektrische stroom erdoorheen kan gaan.

reaction time reactietijd
De tijd tussen het zien van een gevaar en het in werking treden van de remmen.

S

(speed, time) diagram (snelheid,tijd)-diagram
Een grafiek waarin de snelheid is uitgezet tegen de tijd. Wordt ook (v,t)-diagram genoemd.

scan scan
Beeld van het menselijk lichaam dat wordt gemaakt door straling in verschillende richtingen door het lichaam te sturen.

sensor sensor
Onderdeel van een schakeling dat door middel van een elektrisch signaal informatie doorgeeft over de omgeving.

spectrum spectrum
Overzicht waarin verschillende soorten elektromagnetische straling zijn geordend op frequentie.

speed of light lichtsnelheid
Snelheid van het licht, in vacuüm 299 792 458 ($3{,}0 \cdot 10^8$) meter per seconde.

statically charged statisch
Situatie waarin een voorwerp een elektrische lading heeft.

switch schakelaar
Onderdeel van een schakeling dat de stroom in- of uitschakelt.

T

total current totale stroomsterkte
De stroomsterkte in het niet-vertakte gedeelte van een parallelschakeling.

tracer tracer
Radioactieve merkstof. Er kan onderzoek mee worden gedaan naar de werking van specifieke organen. Er kunnen ook tumoren mee worden opgespoord.

transistor transistor
Onderdeel van een schakeling dat fungeert als een automatische schakelaar.

transmission transmissie
Doorlaten van straling door een voorwerp of een hoeveelheid stof.

U

uniform acceleration eenparig versnelde beweging
Een beweging waarvan de snelheid gelijkmatig groter wordt.

uniform deceleration eenparig vertraagde beweging
Een beweging waarvan de snelheid gelijkmatig kleiner wordt.

uniform motion eenparige beweging
Een beweging waarvan de snelheid constant blijft.

V

(v,t) diagram (v,t)-diagram
Een grafiek waarin de snelheid is uitgezet tegen de tijd. Wordt ook (snelheid,tijd)-diagram genoemd.

voltage spanning
Een maat voor hoeveel elektrische energie elk deeltje met zich meedraagt.

W

wavelength golflengte
De afstand tussen twee golftoppen of tussen twee golfdalen.

work arbeid
De hoeveelheid energie die een motor nuttig gebruikt om een massa over een bepaalde afstand te verplaatsen.

X

(x,t) diagram (x,t)-diagram
Een grafiek waarin de plaats is uitgezet tegen de tijd. Wordt ook (plaats,tijd)-diagram genoemd.

X-ray source röntgenbron
Apparaat dat röntgenstraling produceert.

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